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PERFORMANCE OF SOILS UNDER TIRE LOADS.  
REPORT 8. APPLICATION OF TEST RESULTS TO  
TIRE SELECTION FOR OFF-ROAD VEHICLES

G. W. Turnage

Army Engineer Waterways Experiment Station  
Vicksburg, Mississippi

September 1972

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# PERFORMANCE OF SOILS UNDER TIRE LOADS

Report 8

APPLICATION OF TEST RESULTS TO TIRE SELECTION  
FOR OFF-ROAD VEHICLES

by

G. W. Turnage

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13. ABSTRACT Data from a very large block of previously collected data from laboratory single-wheel tests and from selected field tests were examined to: (a) determine whether the dimensionless prediction terms for sand $\frac{G(bd)^{3/2}}{W} \propto \frac{\delta}{h}$ and for clay $\frac{Cbd}{W} \propto \left(\frac{\delta}{h}\right)^{1/2}$ could be improved, and (b) extrapolate laboratory relations to field relations for full-size vehicles. (In these terms C and G are penetration resistance and penetration resistance gradient, respectively, for clay and sand; b is tire width; d is tire diameter; h is section height; $\delta$ is tire deflection; and W is wheel load.) The term for sand and an improved term for clay $\frac{Cbd}{W} \propto \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)}$ were designated the basic prediction terms. These basic terms predict dimensionless tire performance coefficients pull/load (P/W), sinkage/diameter (z/d), torque/load $\cdot$ active radius (M/W <sub>r</sub> ), all at 20 percent slip (near maximum pull), and towed force/load (P <sub>t</sub> /W) quite well for many sizes and shapes of pneumatic tires in the laboratory sands and clay. Other alternative terms examined for both sand and clay predict the performance of tires or wheels of very small $\delta/h$ values more accurately than the basic terms, but predict performance of conventional pneumatic tires less accurately. When dimensionless terms $(150V_w/V_{sh})^{1/2}$ and $[0.1(V_w/b)/(V_s/d_s)]^{0.092}$ are attached to the basic prediction terms for sand and clay, respectively, the P/W versus prediction term relations are effectively collapsed to single lines for wheel translational velocities (V <sub>w</sub> ) in the <1 to 18 ft/sec range. (V <sub>sh</sub> is shear wave velocity, V <sub>s</sub> is standard penetration velocity, and d <sub>s</sub> is diameter of a standard cone.) The basic prediction terms can serve as the base for predicting wheeled vehicle performance in the field if RCI (rating cone index) is substituted for C in the term for clay. Equations that describe the pertinent relations are examined in detail, and examples illustrate several of their many possible applications.		

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## FOREWORD

This report comprises a study of results from laboratory tests previously conducted at the U. S. Army Engineer Waterways Experiment Station (WES) and from field tests from locations in various parts of the United States and the world, as part of the vehicle mobility research program under Department of the Army Project No. 1T062112A046, "Trafficability and Mobility Research," Task 03, "Mobility Fundamentals and Model Studies," under the sponsorship and guidance of the Research, Development and Engineering Directorate, U. S. Army Materiel Command.

The laboratory tests were performed by personnel of the Mobility Research Branch (MRB), Mobility and Environmental (M&E) Systems Laboratory, WES, during the period November 1963 to May 1969 under the general supervision of Messrs. W. G. Shockley and S. J. Knight, Chief and Assistant Chief, respectively, of the M&E Systems Laboratory, and under the direct supervision of Messrs. A. J. Green and J. L. Smith of the Research Projects Group of the MRB. Field data examined herein were obtained from published and unpublished reports of the Vehicle Studies Branch of the M&E Systems Laboratory. Miss M. E. Smith and Mr. Green participated in the data analysis, and Miss Smith and Mr. J. L. McRae assisted in the preparation of many of the plates, figures, and tables. Mr. G. W. Turnage directed the study and prepared this report.

COL Ernest D. Peixotto, CE, was Director of the WES during the course of this study and preparation of this report. Mr. F. R. Brown was Technical Director.

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# NOTATION

$A_c$	Tire contact area on a flat, rigid surface
$b$	Tire section width
$c$	Soil cohesion
$C$	Soil penetration resistance; cone index
$C_s, C_x$	Cone index obtained with a 0.5-sq-in.-base-area, right circular, 30-deg-apex-angle cone at 72 in./min, and cone index obtained at any particular velocity with a cone of any particular base area, respectively
$d$	Tire diameter
$d_s, d_x$	Diameter of a standard 30-deg-apex-angle, right circular, 0.5-sq-in.-base-area cone, and diameter of any particular cone, respectively
$D_r$	Relative density
$f$	Soil-tire coefficient of friction
$g$	Acceleration due to gravity
$G$	Soil penetration resistance gradient
$h$	Tire section height
$l$	Characteristic linear dimension of tire
$M$	Torque
$P, P_{opt}, P_m$	Pull, optimum pull, and towed force, respectively
$r_v$	Average active radius of tire
$s$	Soil shear strength
$V, V_w$	Velocity and wheel translational velocity, respectively
$V_s, V_x$	Standard and particular penetration velocity, respectively
$V_{sh}$	Soil shear wave velocity
$W, W_I, W_{opt}$	Load, immobilization load, and optimum load, respectively
$z$	Tire sinkage
$\gamma$	Soil density
$\delta$	Tire deflection
$\phi$	Soil friction angle

## CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
inches	2.54	centimeters
square inches	6.4516	square centimeters
feet	0.3048	meters
cubic inches	16.3871	cubic centimeters
pounds (force)	4.4482	newtons
pounds per square inch	6.8948	kilonewtons per square meter
pounds per square inch per inch	0.2714	meganewtons per cubic meter
feet per second	0.3048	meters per second

## SUMMARY

This study examined the effects of tire deflection, tire geometry, wheel load, and soil strength on the performance of various single pneumatic tires tested in the laboratory in air-dry sand and near-saturated clay, and on the performance of a solid rubber tire and three rigid metal wheels tested in near-saturated clay and air-dry sand, respectively. Mathematical expressions were developed that combine the independent soil and tire parameters into dimensionless forms that correlate closely with dimensionless tire performance coefficients: pull/load ( $P/W$ ), sinkage/diameter ( $z/d$ ), torque/load times active radius ( $M/Wr_a$ ), all at 20 percent slip or near the maximum pull point, and towed force/load ( $P_T/W$ ).

One basic prediction term  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$  was shown to predict the in-sand performance of pneumatic tires (of both circular and rectangular cross sections) with useful accuracy for a broad range of values of soil strength (penetration resistance gradient  $G$ ), tire section width and diameter ( $b$  and  $d$ , respectively), wheel load ( $W$ ), and tire deflection ( $\delta/h$ ). A basic prediction term  $\frac{Cb d}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)}$  (where  $C$  = soil penetration resistance, an indicator of soil strength) accomplished a similar objective for pneumatic tires in clay.

Alternative prediction terms  $\frac{G(bd)^{3/2}}{W} \cdot \left(1 - \frac{\delta}{h}\right)^{-4}$  for sand and  $\frac{Cb d}{W} \cdot \left(1 - \frac{\delta}{h}\right)^{-2} \cdot \frac{1}{1 + (b/2d)}$  for clay predicted  $P/W$  performance (at 20 percent slip) for pneumatic tires with only slightly less accuracy than the basic prediction terms; these alternative terms predicted the  $P/W$  performance of tires of very small deflection values ( $\delta/h$  less than 0.03) more accurately than the basic prediction terms. Other alternative prediction terms  $\frac{Gbd^2}{W} \cdot \left(1 - \frac{2\delta}{d}\right)^{-8}$  and  $\frac{Cb^{1/2}d^{3/2}}{W} \cdot \left(1 + \frac{4\delta}{d}\right)^4$  eliminate one tire dimension (section height  $h$ ) included in the prediction terms above. They predict  $P/W$  performance for pneumatic tires almost as well as the basic and alternative prediction terms mentioned above, and they predict  $P/W$  performance for essentially nondeflected tires better than any other prediction terms examined herein.

Hard-surface contact area  $A_c$  can be incorporated into a useful dimensionless prediction term for pneumatic tires operating in sand  $[G(A_c)^{3/2}/W]$ .  $A_c$  appears considerably less effective in delineating the effects of tire geometry on pneumatic tire performance in clay.

Increasing wheel translational velocity  $V_w$  (in the <1 to 18 ft/sec range) significantly increases the  $P/W$  performance of pneumatic tires both in sand and in clay. The effect appears independent of tire size in sand and is size dependent (inversely related) in clay.

Empirically developed dimensionless terms  $(150V_w/V_{sh})^{1/2}$  and  $[0.1(V_w/b)/(V_s/d_s)]^{0.092}$  attached as multiplicative factors to  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$  and  $\frac{Cb d}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)}$ , respectively, effectively collapse the  $P/W$  versus prediction term relations to single central lines. (In the terms above  $V_{sh}$  is soil shear wave velocity,  $V_s$  is standard penetration velocity, and  $d_s$  is diameter of a standard cone.)

Slight differences between the  $P/W$  versus  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$  relations for two air-dry, coarse-grained soils (Yuma and mortar sand) indicate that sand-tire interactions are influenced somewhat by sand properties not measured by penetration resistance gradient  $G$ . Adjusting values of  $G$  for mortar sand to  $G$  values for Yuma sand on the basis of relative density effectively eliminated differences between the central relations.

Flooding the surface of a near-saturated, fine-grained soil reduces the  $P/W$  performance of pneumatic tires with tread or traction aid (attached steel or rubber cleats) considerably, and that of smooth tires by an even larger amount. Type of tread had more influence on  $P/W$  for the unflooded than the flooded condition, but only the tire with traction aid significantly outperformed the smooth tire in the unflooded environment.

An analysis of multiple-pass tests illustrates that single-wheel pneumatic tire performance in sand on the second and third passes is related to  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$ , although the relation is not the same as that for the first pass. It is shown that the performance of wheeled vehicles on coarse-grained soils can be predicted using a relation based on the single-wheel, multiple-pass relations. Multiple-pass, single-wheel laboratory tests in a near-saturated fine-grained soil indicate that traffic negligibly influences pneumatic tire performance.

Field tests of wheeled vehicles produced pull performance significantly worse than that obtained in the laboratory, largely because of the negative influence of several largely uninvestigated factors--primarily irregular soil profiles, slipperiness (for fine-grained soils),

operating characteristics peculiar to a wheeled vehicle (as opposed to a single wheel), and several others discussed in the text.

Basic prediction terms  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$  and  $\frac{Cbd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)}$  adequately collapse large blocks of field pull-performance data for wheeled vehicles in sand and clay, respectively, to central relations. These relations are sufficiently well defined and broadly based to provide the basis for a tentative wheeled vehicle performance prediction system (e.g. immobilization load, load required to produce maximum pull, maximum slope climbable, etc., can be predicted) and a method of designing tires to satisfy particular off-road situations. Parts III and IV of the report develop and describe these relations, and Appendix B illustrates several applications.

Appendix A describes the techniques used in this report to compute sand strength, wheel load, and pneumatic tire sinkage. These and every other parameter discussed herein were each measured by a consistent method to allow data from a variety of sources to be described on a common basis.

## PERFORMANCE OF SOILS UNDER TIRE LOADS

### APPLICATION OF TEST RESULTS TO TIRE SELECTION FOR OFF-ROAD VEHICLES

#### PART I: INTRODUCTION

##### Background

1. Until the early 1960's, research in the United States in vehicle mobility was confined largely to experimental testing of full-sized vehicles on natural terrain surfaces to develop approximate relations between vehicle performance and terrain conditions for use by military commanders in the field. In 1960, following a study of the status of mobility research in the United States by an ad hoc committee appointed by the Chief of Research and Development, U. S. Army, authority was granted the U. S. Army Engineer Waterways Experiment Station (WES) to equip a modern laboratory and initiate a long-term program in vehicle mobility research. Since then, many systematic tests have been performed with single pneumatic tires in controlled-soil conditions, and certain peripheral studies have been conducted that were designed to further a basic understanding of tire-soil interactions. Additionally, a limited number of vehicle tests have been conducted in the laboratory, and results of a large number of field vehicle tests have been analyzed on the basis of relations developed from the laboratory test data.

##### Purpose and Scope

2. The basic purpose of the study reported herein is to provide a rational means for selecting tires for off-road vehicle use. Two types of soils were considered: those that derive essentially all their strength from cohesion and those that gain nearly all their strength from friction. (These soil types generally cause more severe mobility problems for wheeled vehicles than do soils whose strength results from a combination of cohesion and friction.) For each of the two types of soil, one basic dimensionless term has been developed that can be used

to quantitatively describe the effects on wheeled vehicle tractive performance of wheel load, soil strength, tire size, tire shape, and tire deflection (in lieu of inflation pressure) for a very broad range of soil-tire conditions commonly encountered in the field. Additionally, for each soil type, at least two dimensionless terms are presented that have some advantage over the basic terms in predicting the performance of tires and wheels of particular, unusual configurations (e.g. very small tire deflections, tires or wheels with no measurable section heights, etc.).

3. The prediction terms were developed primarily from a distillation of data obtained in single-wheel tests under the program "Performance of Soils Under Tire Loads," sponsored by the U. S. Army Materiel Command. However, to the extent possible, the results of tests in natural soils with actual vehicles have also been analyzed, and the prediction techniques for laboratory data have been altered as necessary to satisfy the field-prototype vehicle situation.

4. Tire performance was measured in terms of four dependent parameters: (a) pull, (b) sinkage, and (c) torque--all at near the maximum-pull point; and (d) the force required to tow the unpowered wheel.

#### Definitions

5. Certain terms that facilitate analysis of data and communication of test results are rigorously defined in Report 1 of this series.<sup>1</sup> Only those additional terms that are considered essential to this report are defined below.

- a. Active radius ( $r_a$ ),\* in.\*\*: The undeflected tire radius  $r$  minus half the deflection  $\delta$  of the tire loaded on a

---

\* Since reference 1 was published, it has been determined that relations between dimensionless prediction terms (composed of functions of the independent tire, soil, and system parameters) and the torque coefficient are improved if active radius  $r_a$  is used in place of diameter in the torque coefficient, i.e.  $\frac{M}{Wr_a}$  is preferred to  $\frac{M}{Wd}$ .

\*\* A table of factors for converting British units of measurement to metric units is given on page xi.

hard, rigid surface, i.e. half the diameter minus deflection  $\left(\frac{d - \delta}{2}\right)$ . Empirically obtained,  $r_a$  is a significant measurement since tire rolling circumference measured on a hard surface is very closely approximated by the quantity  $2\pi \cdot \frac{d - \delta}{2}$ .

- b. Penetration resistance gradient (G), psi/in.: For coarse-grained soils (sands), the slope of the curve of penetration resistance (for a 0.5-sq-in.-base-area, 30-deg-apex angle, right circular cone at 72-in./min penetration speed) versus depth, averaged over that depth within which changes in soil strength significantly affect tire performance (usually taken as 6 in.).
- c. Towing force (maximum drawbar pull), lb: The maximum sustained towing force a self-propelled vehicle can produce at its drawbar under given test conditions. (Note: Towing force-load ratio approximates maximum slope negotiable.)
- d. Nominal dimensions from tire size designation:
  - (1) Conventional, circular-cross-section pneumatic tires:
    - (a) Section width (b), in. Maximum outside width of the cross section of the inflated, but unloaded, tire. Nominally specified by the first number in the tire size designation, e.g. 9.00 in the 9.00-14 tire.
    - (b) Nominal rim diameter, in. Diameter measured from shoulder to shoulder of the rim. Given as the second number in the tire size designation, e.g. 14 in the 9.00-14 tire.
    - (c) Diameter (d), in. Outside diameter of the inflated, but unloaded, tire. For circular-cross-section tires, nominal rim diameter plus twice the section width usually overestimates diameter  $d$  of a buffed-smooth tire somewhat (usually by some 5 to 20 percent).

(2) Rectangular-cross-section pneumatic tires:

- (a) Diameter (d), in. An approximation of tire diameter  $d$  (defined above) that is specified by the first number in the size designation, e.g. 16 in the 16x15.00-6 tire.
- (b) Section width (b), in. An approximation of tire section width  $b$  (defined above) that is given by the second number in the tire size designation, e.g. 15.00 in the 16x15.00-6 tire.
- (c) Nominal rim diameter, in. An approximation of rim diameter (defined above) that is listed as the third number in the tire size designation, e.g. 6 in the 16x15.00-6 tire.

e. Immobilization point: That point at which wheel load becomes too large and/or soil strength too weak to allow a tire of given size and deflection to develop positive pull.

## PART II: PREDICTING IN-SOIL, SINGLE-WHEEL PERFORMANCE

6. To measure the effectiveness of the wheel as a traction and/or transport element and to determine quantitatively the effects on tire performance of the parameters that describe the soil-tire system, the wheel was isolated and tested as a separate entity. Several dynamometer carriages were constructed to accommodate a large variety of tire sizes and wheel loads, and laboratory tests were conducted in which a broad range of values of soil strength, tire size, tire shape, wheel load, and speed were systematically varied.

### Parameters Considered

7. A dimensional analysis<sup>2</sup> of the performance of single, pneumatic tires in soft soils determined that the four dependent tire performance parameters of primary interest (paragraph 4) are related to independent tire, soil, and system parameters in dimensionless form as follows:\*

a. For the pull coefficient:

$$\frac{P}{W} = f' \left( \frac{\delta}{h}, \frac{b}{d}, \frac{h}{d}, \phi, s, f, \frac{cl^2}{W}, \frac{\gamma l^3}{W}, \frac{v^2}{gl}, \frac{W}{blv} \right)$$

b. For the sinkage coefficient:

$$\frac{z}{d} = f'' \left( \frac{\delta}{h}, \frac{b}{d}, \frac{h}{d}, \phi, s, f, \frac{cl^2}{W}, \frac{\gamma l^3}{W}, \frac{v^2}{gl}, \frac{W}{blv} \right)$$

c. For the torque coefficient:

$$\frac{M}{Wr_a} = f''' \left( \frac{\delta}{h}, \frac{b}{d}, \frac{h}{d}, \phi, s, f, \frac{cl^2}{W}, \frac{\gamma l^3}{W}, \frac{v^2}{gl}, \frac{W}{blv} \right)$$

d. For the towed force coefficient:

---

\* For definition of terms see Notation, page ix.

$$\frac{P_T}{W} = f^{(10)} \left( \frac{\delta}{h}, \frac{b}{d}, \frac{h}{d}, \phi, s, f, \frac{cl^2}{W}, \frac{\gamma l^3}{W}, \frac{v^2}{gl}, \frac{W}{blV} \right)$$

8. The 10 dimensionless pi terms in parentheses in each of the relations above are considered sufficient to describe practically any tire-soil-system arrangement if these independent pi terms are properly combined. Test controls and simplifying assumptions can be used to reduce to a much smaller value the number of independent pi terms that must be considered for a particular situation. In published reports to date, the four dependent pi terms have been related to the independent pi terms in two environments, in each of which only three independent pi terms had to be considered:

a. For saturated, highly plastic, essentially purely cohesive clay:

$$(1) \frac{P}{W} = f' \left( \frac{cl^2}{W}, \frac{b}{d}, \frac{\delta}{h} \right)$$

$$(2) \frac{z}{d} = f'' \left( \frac{cl^2}{W}, \frac{b}{d}, \frac{\delta}{h} \right)$$

$$(3) \frac{M}{Wr_a} = f''' \left( \frac{cl^2}{W}, \frac{b}{d}, \frac{\delta}{h} \right)$$

$$(4) \frac{P_T}{W} = f^{(4)} \left( \frac{cl^2}{W}, \frac{b}{d}, \frac{\delta}{h} \right)$$

b. For air-dry, essentially purely frictional sand:

$$(1) \frac{P}{W} = f' \left( \frac{Gl^3}{W}, \frac{b}{d}, \frac{\delta}{h} \right)$$

$$(2) \frac{z}{d} = f'' \left( \frac{Gl^3}{W}, \frac{b}{d}, \frac{\delta}{h} \right)$$

$$(3) \frac{M}{Wr_a} = f''' \left( \frac{Gl^3}{W}, \frac{b}{d}, \frac{\delta}{h} \right)$$

$$(4) \frac{P_T}{W} = f^{(4)} \left( \frac{Gl^3}{W}, \frac{b}{d}, \frac{\delta}{h} \right)$$

#### Laboratory Single-Wheel Test Program

##### Laboratory test soils and their characteristics

9. The principal soils used in this laboratory program were a

fine, air-dry, essentially frictional desert sand (Yuma sand) and a saturated, highly plastic, essentially purely cohesive fat clay. A second coarser-grained, air-dry, frictional riverbed sand (mortar sand) was used for a limited number of tests. Grain-size distribution curves for these three soils are presented in fig. 1.

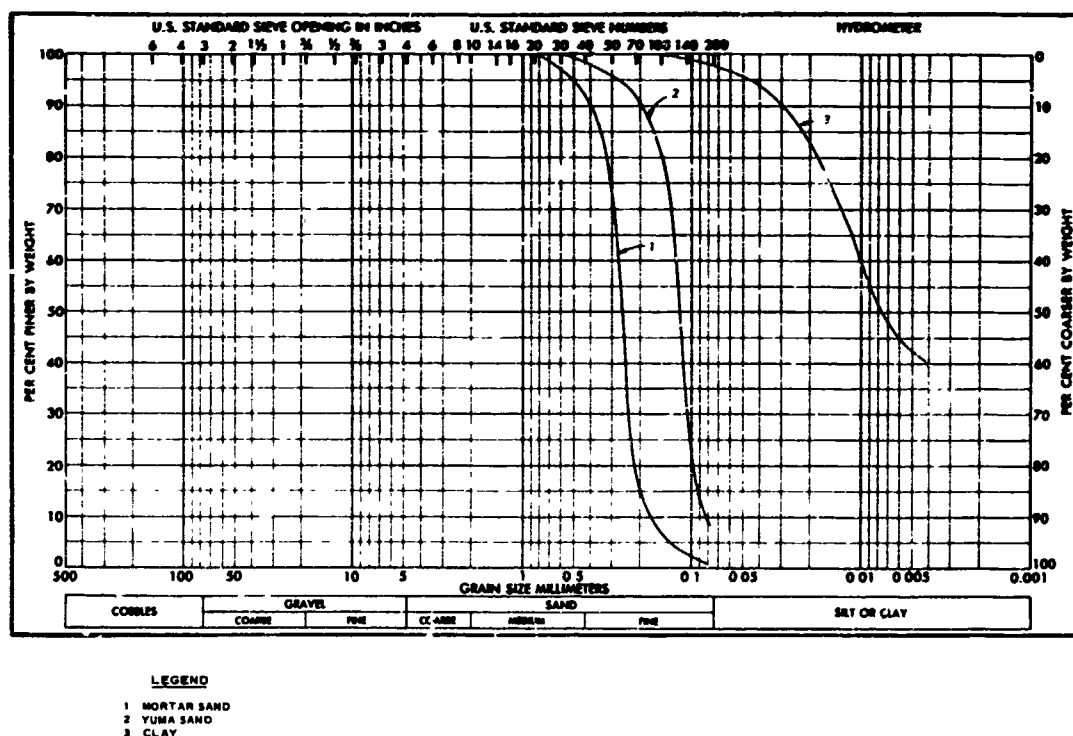


Fig. 1. Grain-size distributions of the laboratory test soils

10. Strength of each of the three test soils was characterized in the relations reported herein from data obtained in standard 72-in./min penetration tests with the WES 0.5-sq-in. circular-base-area, 30-deg-apex-angle cone. Test beds of both Yuma and mortar sands were constructed such that values of cone index (i.e. penetration resistance in pounds divided by cone base area) increased linearly with depth, as illustrated by fig. 2a for Yuma sand. Penetration resistance gradient  $G$  (i.e. the slope of the linear portion of the penetration resistance versus depth curve) characterized the strength of sand.<sup>2,3</sup> Test beds of clay were constructed such that values of cone index remained essentially constant as depth of penetration increased (fig. 2b). Average

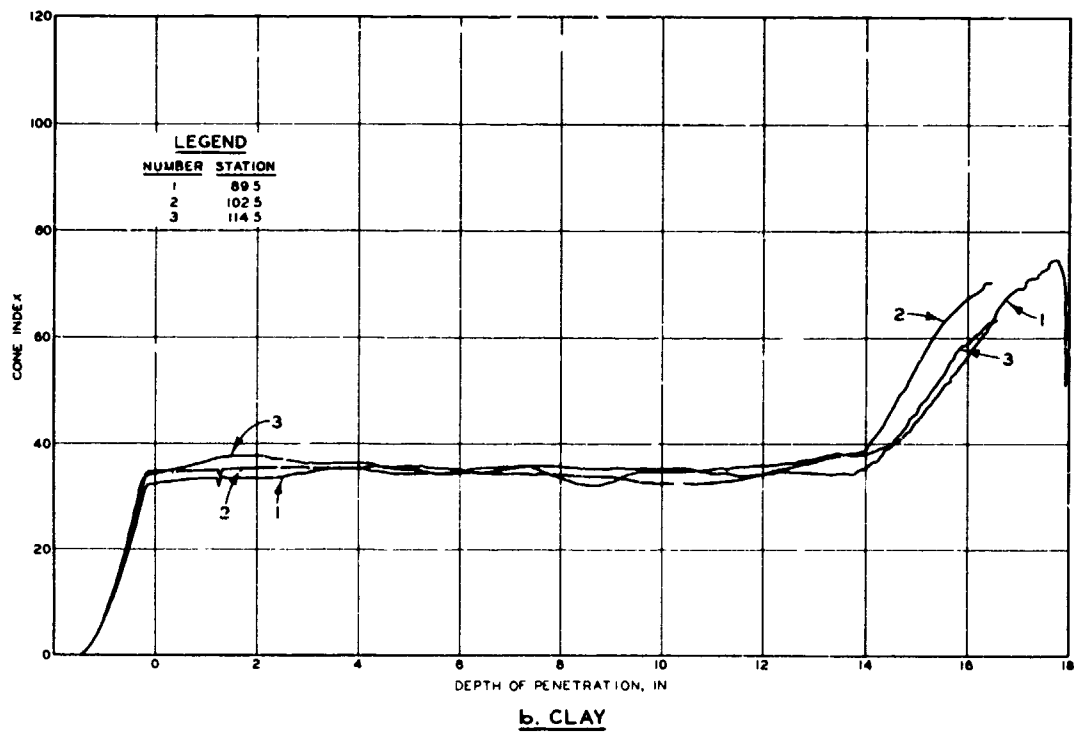
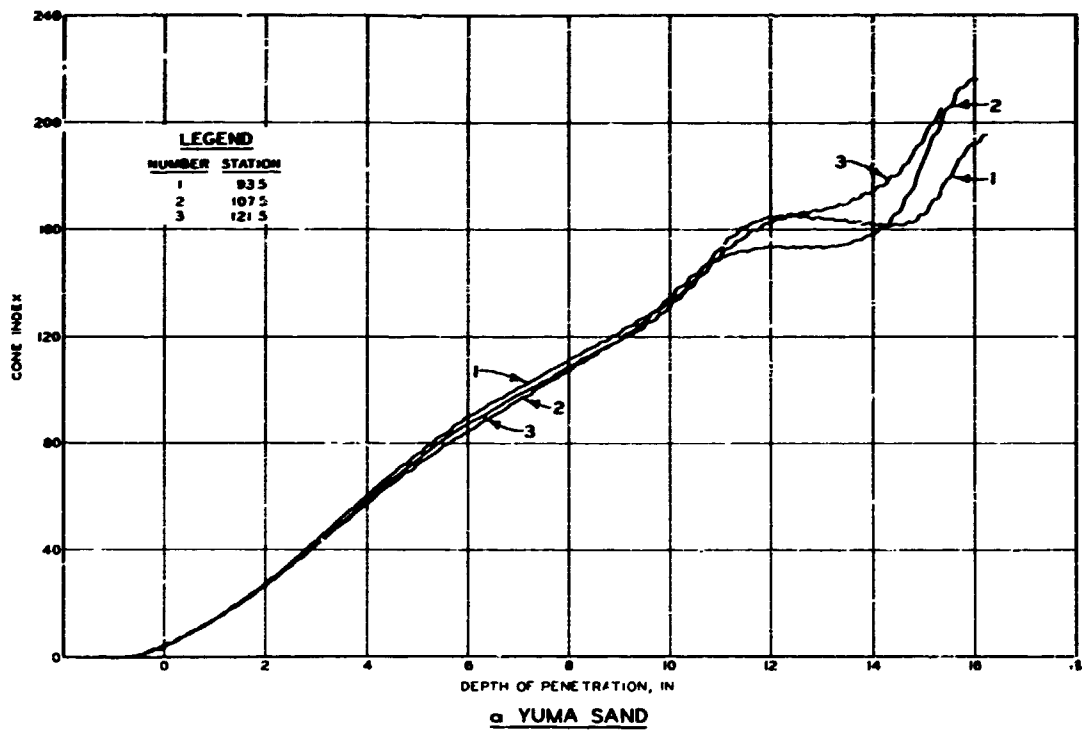


Fig. 2. Sample recordings of cone penetration tests

cone index  $C$  in the top 0- to 5-in. layer was used to describe clay soil strength.

11. Several experimenters have shown that for cohesionless, dry sand friction angle  $\phi$  is proportional to density  $\gamma$ .<sup>4,5</sup> Thus,  $\phi$  was eliminated as a separate parameter in paragraph 8. Also, it has been determined that penetration resistance gradient  $G$  is directly related to and is a sensitive indicator of density  $\gamma$  of a frictional soil. Parameter  $G$ , then, was indicated sufficient to describe frictional soil characteristics attributable to both  $\phi$  and  $\gamma$ , and  $G$  has been used to describe the effects of  $\phi$  and  $\gamma$  in earlier reports.<sup>2,3</sup> For purely cohesive soils, cone index  $C$  is considered to represent soil cohesion  $c$ . Detailed laboratory tests<sup>6</sup> have demonstrated that for saturated, weak, essentially frictionless soils (values of  $C$  up to about 80) a well-defined linear relation exists between cone index and cohesion.

12. For the laboratory frictional sand soils, the value of penetration resistance gradient  $G$  changed under the influence of tire traffic. In every case, however, the before-traffic measure of  $G$  was used to describe the strength of a sand test section. For the laboratory clay soil, it was determined that the cone index value is virtually unaffected either by changes in wheel slip or by tire traffic (for at least five passes, as were routinely made in the laboratory tests). For the laboratory tests, cone index measurements were usually taken at three locations for each of passes 0 (i.e. before traffic), 1, 2, and 5. The cone index value reported herein is the average of values measured for all of these locations and passes (usually a total of 12 measurements). This value is considered to be a reasonable characterization of soil strength within the overall length of the test lane and may be related to either a single pass or multiple passes of a wheel.

#### Test techniques

13. Most WES laboratory tests of pneumatic tires in sand and in clay have been conducted as programmed-increasing-slip tests. This technique produces a wealth of information per test. Furthermore, the results obtained at any particular value of slip in a programmed-slip test

in either sand or clay are essentially the same as those that would be developed in a corresponding constant-slip test, if the value of wheel pull is corrected to account for the effect of the inertial force ( $F = ma$ ) caused by the constant deceleration of the dynamometer carriage during the test run. A detailed description of the programmed-increasing-slip test technique and the correction that is now made for this inertial effect is given in Appendix A. Unfortunately, the need for an  $ma$  correction was not recognized early in the test program, and a number of tests were conducted in which no instrumentation was present to measure  $ma$ . Examination of  $ma$  values from later tests (fig. A6 of Appendix A) shows that in fat clay,  $ma$  values are quite small (none greater than 8 lb for even the largest tire tested) and are relatively independent of both tire size and wheel load. In sand, only one  $ma$  value greater than 7 percent of wheel load was obtained; and in clay, no  $ma$  value greater than 4 percent of wheel load was obtained. Patterns of  $ma$  versus load are not sufficiently well defined, however, to establish a reliable a posteriori  $ma$  correction for those early tests in which  $ma$  was not measured. Throughout this report, wheel pull obtained in a constant-slip or constant-pull test (no  $ma$  correction is needed) or in a programmed-increasing-slip test with the proper  $ma$  correction is denoted as  $P$  (and  $P_T$  for a towed test); wheel pull that includes  $ma$  as part of its value is designated  $P'$  (and  $P'_T$  for the towed point). The values of  $P'$  and  $P'_T$  are algebraically equal to or greater than  $P$  and  $P_T$ , respectively.

14. The programmed-increasing-slip technique produces pull-slip and torque-slip curves that have characteristically different shapes for sand and clay (figs. 3a and 3b). In particular, the influence of the shapes of the pull-slip curves on the selection of where the near-maximum pull condition should be sampled is quite important. For cohesionless sand, the value of pull usually peaks at about 20 percent slip, then decreases gradually as values of slip increase over a broad range, and finally increases again at very large values of slip. For frictionless clay, the value of pull increases rapidly to a value of slip slightly less than 20 percent, and then increases very slowly as values

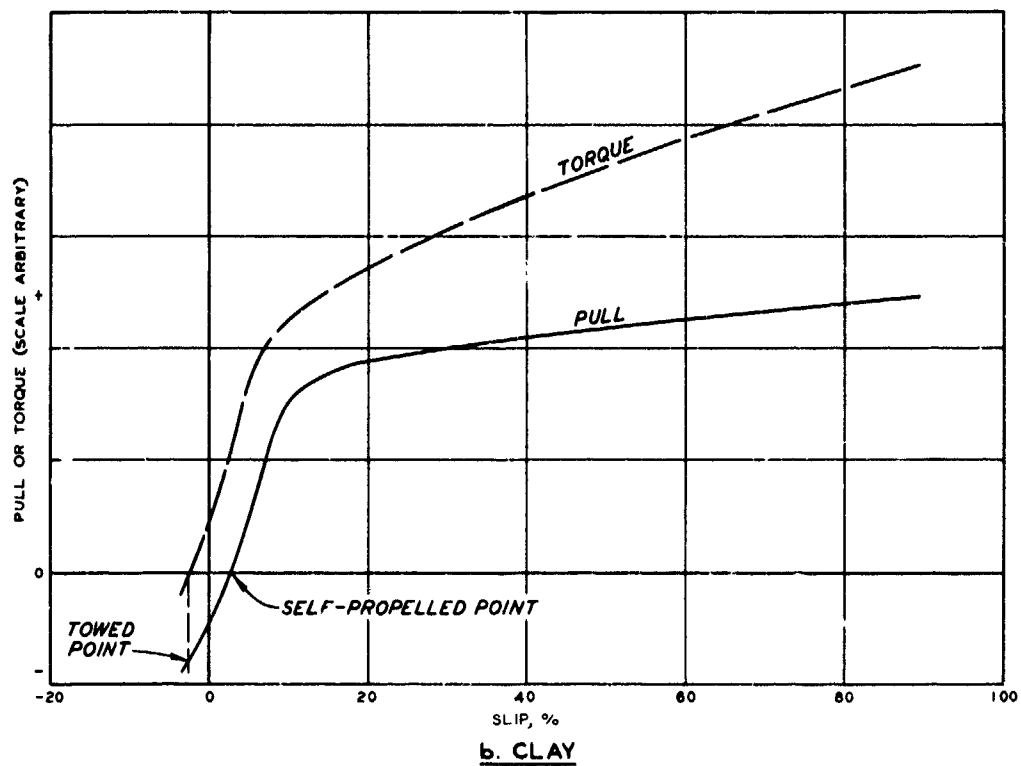
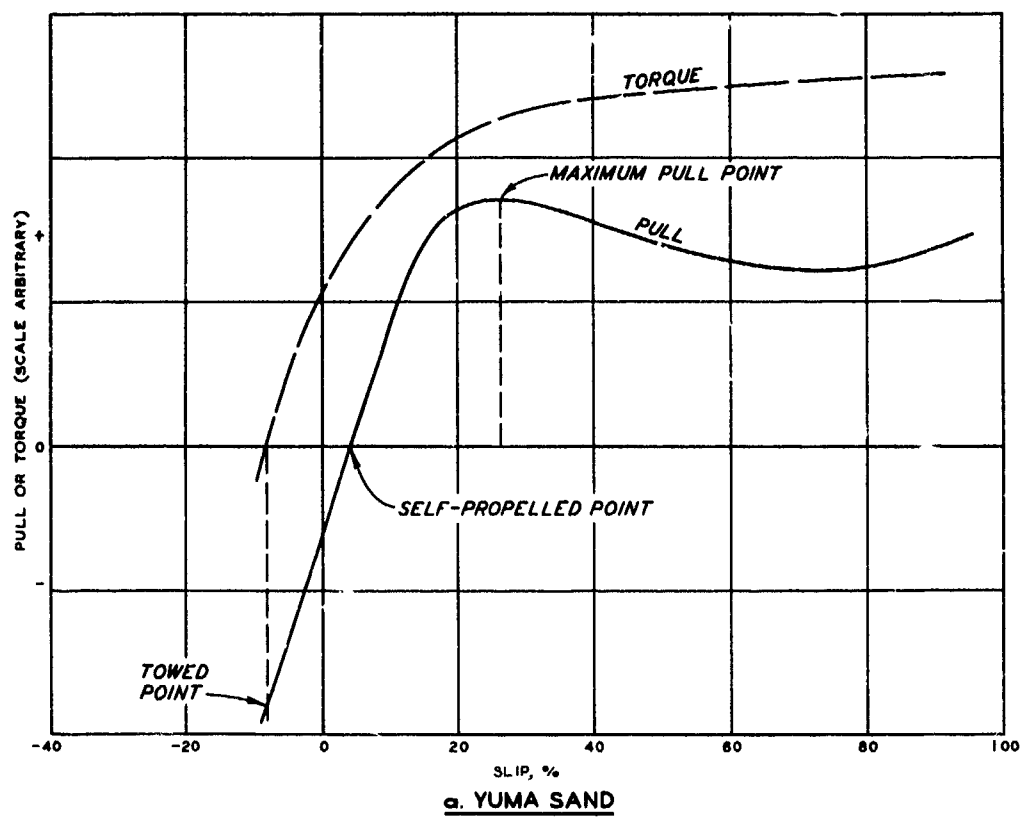


Fig. 3. Sample pull-slip and torque-slip curves

of slip continue to increase. For single-wheel laboratory tests in both sand and clay, the near-maximum-pull condition is characterized in this report by data measured at 20 percent slip.

#### Test tires and test results

15. Characteristics of the pneumatic tires used in this report to study single-wheel laboratory performance in sand and in clay are presented in table 1. A few laboratory tests were made with rigid wheels in sand and with a solid rubber tire in clay; descriptions of these wheels also are given in table 1.

16. Results of the single-wheel laboratory tests in sand that are examined herein are summarized in tables 2-5, 9, and 10; those of single-wheel tests in clay are found in tables 6-8. Data from wheeled vehicle tests conducted in the laboratory (in sand) are presented in table 11; data from vehicle tests made in the field are listed in tables 12 and 13 for sand and 14 and 15 for clay. Except for the results listed in tables 4 and 8, all of the data examined herein were extracted from earlier WES reports of these tests. The same degree of precision was not used in all of the source reports in measuring all of the parameters examined herein. This report attempts to present values of each parameter (from laboratory tests) measured in a uniform way that is similar to that possible in the field. In particular, tire deflection measurements reported herein are those measured on an unyielding, flat surface prior to testing; reported soil strength measurements describe the before-traffic condition (and the during-traffic condition for clay - see paragraph 12); and wheel load values are those measured in the soil at the same instant that the dependent parameters were measured. (Wheel load was applied pneumatically for most of the laboratory tests, and its value varied slightly during each test run.) A single technique was used to obtain penetration resistance gradient  $G$  for coarse-grained soils, as opposed to several types of measurements used in the source reports. Appendix A describes the several approximations of  $G$ , and the means used to transform them to the true gradient (or slope) of the cone index versus penetration depth curve. Appendix A also describes

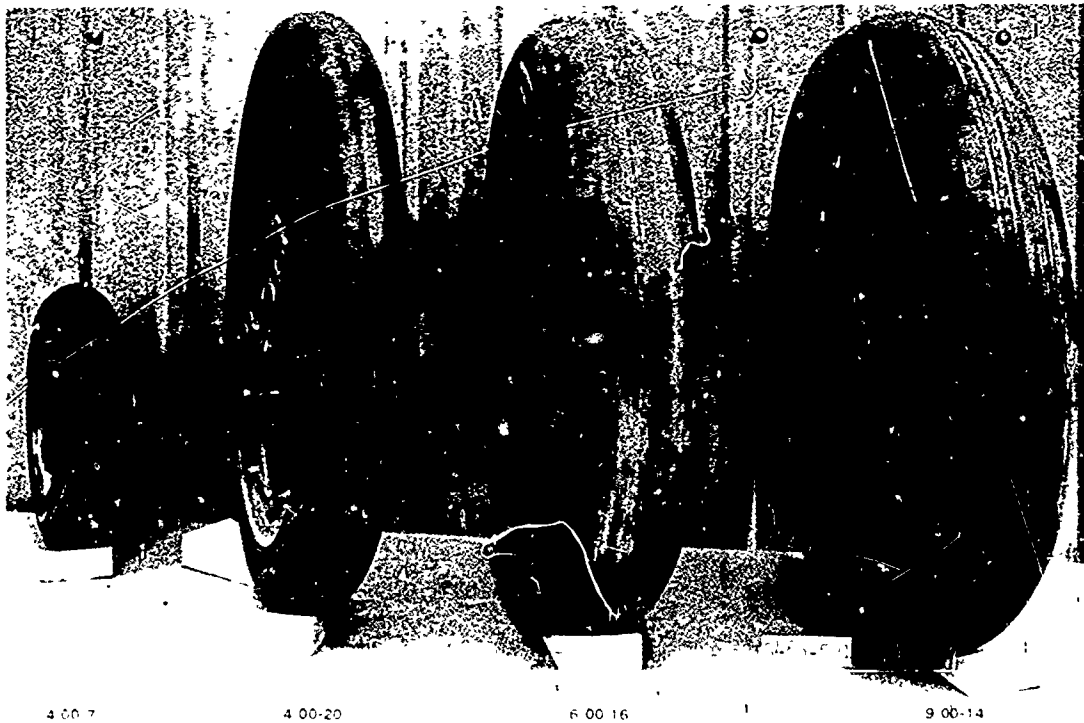
the consistent method by which values of tire sinkage were obtained for this report.

### Tires and Wheels in Sand

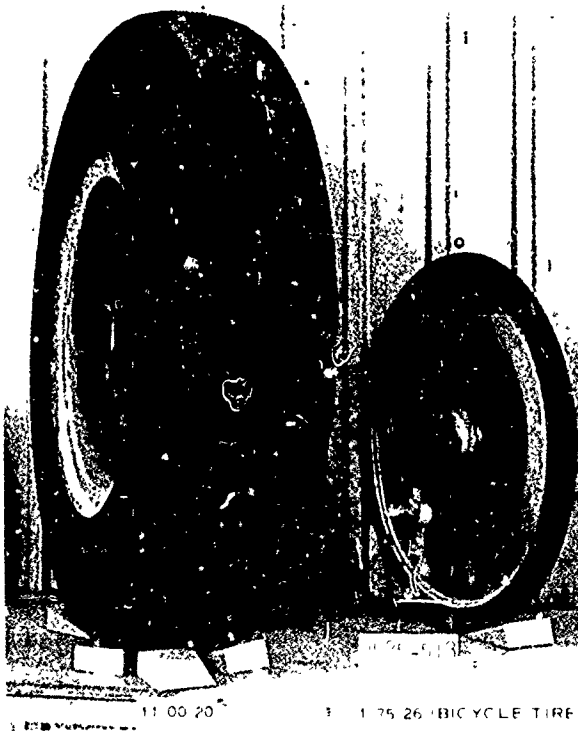
#### Basic prediction term

17. The dimensional analysis in references 2 and 3 combined three independent pi terms-- $Gd^3/W$ ,  $b/d$ , and  $\delta/h$ --on the basis of their relation to four dependent pi terms-- $P'/W$ ,  $z/d$ ,  $M/Wr_a$ , and  $P'_T/W$ --to develop a single dimensionless prediction term,  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$ , referred to in those reports as the sand mobility number and hereafter in this report as the basic prediction term for sand. The basic prediction term was developed using data from single-wheel laboratory tests conducted in one soil (air-dry Yuma sand) at a single translational velocity (approximately 5 ft/sec) with four tires of one general shape (conventional, circular-cross-section tires with  $d/b$  ratios in the 3 to 8 range). These four basic test tires were the 4.00-7, 2-PR; 4.00-20, 2-PR; 6.00-16, 2-PR; and 9.00-14, 2-PR (fig. 4a). Test data for two validation test tires, a 1.75-26 bicycle tire and an 11.00-20, 12-PR tire (fig. 4b), confirmed that relations developed for the basic test tires could also be used for conventional tires with very large values of  $d/b$  and large values of  $d$  and  $b$ , respectively. A later study examined the ability of the basic prediction term to predict the performance of five tires whose cross-sectional shape was roughly rectangular (as opposed to the circular cross sections of the conventional tires) and whose  $d/b$  values ranged from 1 to 2.5.<sup>7</sup> The effectiveness of the basic prediction term in predicting  $P'/W$ ,  $z/d$ ,  $M/Wr_a$ , and  $P'_T$  for the basic test tires, the validation test tires, and the tires in reference 7 is illustrated in plate 1.

18. In addition to  $b$  and  $d$ , each of the other parameters included in the basic prediction term was tested over a broad range of conditions. Values of  $G$  ranged from 2.3 to 27.7 psi/in., virtually the entire range of interest in wheeled vehicle mobility problems. Most



a. Basic test tires



b. Validation test tires

Fig. 4. Basic and validation test tires

of the data were obtained from tests in which penetration resistance increased linearly to the 11- to 12-in. depth; for the 11.00-20, 12-PR tire tests, penetration resistance increased linearly to only the 8-in. depth. Also, test data not included herein, but reported in reference 3, demonstrated that the basic prediction term predicted pneumatic tire performance quite well for tests in which penetration resistance increased linearly to even lesser depths (6 in. for the 9.00-14, 2-PR tire and 7 in. for the 16x15.00-6, 2-PR tire). Values of load in plate 1 ranged from 100 to 1350 lb and values of  $\delta/h$  from 0.15 to 0.35.

19. For three of the four relations presented in plate 1, all of the data points intermingle within a narrow scatter band, strongly indicating that the basic prediction term can be used to predict in-sand pneumatic tire performance for a very broad range of tire, soil, and load conditions. The basic prediction term versus torque coefficient relation appears to separate as a function of tire shape, with the circular-cross-section tires (open symbols) requiring a slightly smaller value of torque coefficient than the rectangular-cross-section tires (closed symbols) at corresponding values of the basic prediction term. For most applications, this deficiency is considered minor, since the separation by tire shape is slight, and torque coefficient is less sensitive to changes in the basic prediction term than any of the other three performance coefficients. (Depending on the accuracy required, the user could characterize the relation by a single central line (i.e. a line of best fit) or by the two lines in plate 1c.) As shown in plate 2, the relations between the basic prediction term and  $P/W$  and  $P_T/W$  (pull and towed force coefficients whose values have been corrected to take into account the influence of inertial effects; see Appendix A) are described by data that lie within narrow scatter bands, i.e. the basic prediction term is closely related to  $P/W$  and  $P_T/W$ . Taken together, the relations in plates 1 and 2 demonstrate that the basic prediction term is sufficiently closely related to the four performance coefficients to allow useful predictions of tire performance.

#### Alternative prediction terms

20. The basic prediction term  $\frac{G(b\delta)^{3/2}}{W} \cdot \frac{\delta}{h}$  is considered to

provide more accurate predictions of in-sand pneumatic tire performance for tire-soil conditions routinely encountered in the field than are provided by any other available term. Alternative terms have been developed, however, that are more useful for particular, special situations. The effectiveness of these terms is examined herein only on the basis of their ability to predict near-maximum pull coefficient; conclusions made on this basis also generally apply to the effectiveness of the alternative terms in predicting the other three performance coefficients--sinkage, torque, and towed force.

21.  $\frac{G(b\delta)^{3/2}}{W} \cdot \left(1 - \frac{\delta}{h}\right)^{-4}$ . This term was developed in the same way as the basic prediction term, except that  $1 - \frac{\delta}{h}$  was used in place of  $\delta/h$ . This was done primarily to obtain a term that could predict the in-sand performance of tires or wheels with deflection values near or equal to zero. The need for an alternative prediction term for this situation is demonstrated in plate 1a; for  $\delta/h \approx 0$  the value of the basic prediction term is approximately zero, and the relation in plate 1a predicts a negative value of  $P'/W$ . Analysis in paragraph 22 shows this prediction to be in error, since relatively large positive values of  $P'/W$  were obtained in several tests of rigid metal wheels ( $\frac{\delta}{h} \approx 0$ ).

22. Data from tests of rigid wheels were used in the development of  $\frac{G(b\delta)^{3/2}}{W} \cdot \left(1 - \frac{\delta}{h}\right)^{-4}$  because no single-wheel tests have been conducted in sand at the WES with pneumatic tires at values of  $\delta/h$  less than 0.15. Because the rigid wheels experienced essentially zero deflection under the test loads used, it was possible to assign to each of them a value of  $1 - \frac{\delta}{h} = 1.0$ . If the performance of tires (or wheels) with zero deflection and with  $\delta/h = 0.15$  can be predicted by a given prediction term, it is reasonable to expect that this term can also be used to predict the performance of tires with values of  $\delta/h$  in the 0 to 0.15 range. Plate 3a shows data from the same tests represented in plate 1, together with test data for the three rigid wheels, to illustrate the effectiveness of this modified prediction term in predicting

near-maximum pull. The pneumatic tire test data were obtained at 20 percent slip, and those for the rigid wheels at 25 percent slip; the influence of this slight deviation on the relation is considered negligible. The penetration resistance gradient  $G$  for each pneumatic tire test is characterized by the average of several pretest measurements for that particular test; only one value of  $G$  was reported<sup>8</sup> to describe the strength of the several sand sections in which the rigid wheels were tested. This undoubtedly contributed to the scatter of the rigid-wheel data, but did not obscure the trends in plate 3a. This alternative prediction term collapses all the pneumatic tire data to a single relation almost as well as the basic prediction term did in plate 1. However, using the modified term to collapse the rigid-wheel data to the same relation as the pneumatic tire data was only partially successful. Data for the 6- by 28-in. and 12- by 28-in. wheels fall generally within the scatter band of the pneumatic tire data, but appear to develop values of  $P'/W$  slightly on the low side for large values of the alternative prediction term. The alternative term predicts values of  $P'/W$  for the 3- by 28-in. wheel significantly larger than those of the remaining tires and wheels. Plate 3b shows the same relation as plate 3a, using only wheel pull data either unaffected by or corrected for inertial effects. Thus,  $\frac{G(bd)^{3/2}}{W} \cdot \left(1 - \frac{\delta}{h}\right)^{-4}$  can be considered a useful term for predicting the in-sand, near-maximum pull performance of pneumatic tires with a very broad range of values of  $b$ ,  $d$ , and  $1 - (\delta/h)$ ; however, care must be exercised in using this term to predict the performance of tires and wheels having very small values of both  $\delta/h$  and  $b/d$ . Generally speaking, this combination of characteristics should be avoided in the design of a tire or wheel for mobility purposes, so this restriction in the use of this alternative prediction term is not severe.

23.  $\frac{Gb d^2}{W} \cdot \left(1 - \frac{2\delta}{d}\right)^{-8}$ . This term was developed in a performance evaluation of wheels for lunar vehicles,<sup>9</sup> wherein a prediction term was sought that would relate data for pneumatic wheels, rigid wheels, and metal-elastic wheels equally well. A desirable feature of this

prediction term was the elimination of the term  $h$  (paragraph 21), thereby (a) permitting the tire or wheel to be described by one less term, and (b) allowing the prediction of performance for tires or wheels that do not have section heights. Five basic wheels (fig. 5) were tested under very light loads (15 to 150 lb) in air-dry and in moist Yuma sand. Several prediction terms were tried and tested (by plotting them versus performance coefficients from all the lunar study tests), the visual lines of best fit were drawn, and the scatter of the data was observed.  $\frac{Gbd^2}{W} \cdot \left(1 - \frac{2\delta}{d}\right)^{-8}$  was selected as the most effective prediction term for the conditions of the study. Practically all of the tests in the lunar study were described by values of this prediction term larger than 1000 (and up to 23,000), primarily because of the very light wheel loads. Normal earthbound loading of wheels produces much smaller values of this prediction term, as demonstrated in plate 4a, where the data for pneumatic tires intermingle and lie within a scatter band only slightly larger than that in plate 1a. Taken together, the rigid-wheel data lie somewhat higher than the pneumatic tire data at values of the prediction term less than about 150 and slightly lower than the pneumatic tire data at higher values of the prediction term. However, data for the 3- by 28-in. wheel lie much more nearly within the scatter band in plate 4a than they do in plate 3a; and, taken as a whole, the  $P'/W$  values of the rigid wheels appear to more nearly fit the central relation for pneumatic tires when predicted by  $\frac{Gbd^2}{W} \cdot \left(1 - \frac{2\delta}{d}\right)^{-8}$  than when predicted by  $\frac{G(bd)^{3/2}}{W} \cdot \left(1 - \frac{\delta}{h}\right)^{-4}$ . Plate 4b demonstrates

that the former prediction term is closely related to  $P/W$ ; comparison of plates 4a and 4b shows that slightly smaller algebraic values of  $P/W$  than of  $P'/W$  are obtained for corresponding values of this prediction term.

24. In summary,  $\frac{Gbd^2}{W} \cdot \left(1 - \frac{2\delta}{d}\right)^{-8}$  predicts in-sand pneumatic tire performance for a wide range of tire shapes, sizes, and deflections with reasonable accuracy and predicts rigid-wheel performance with

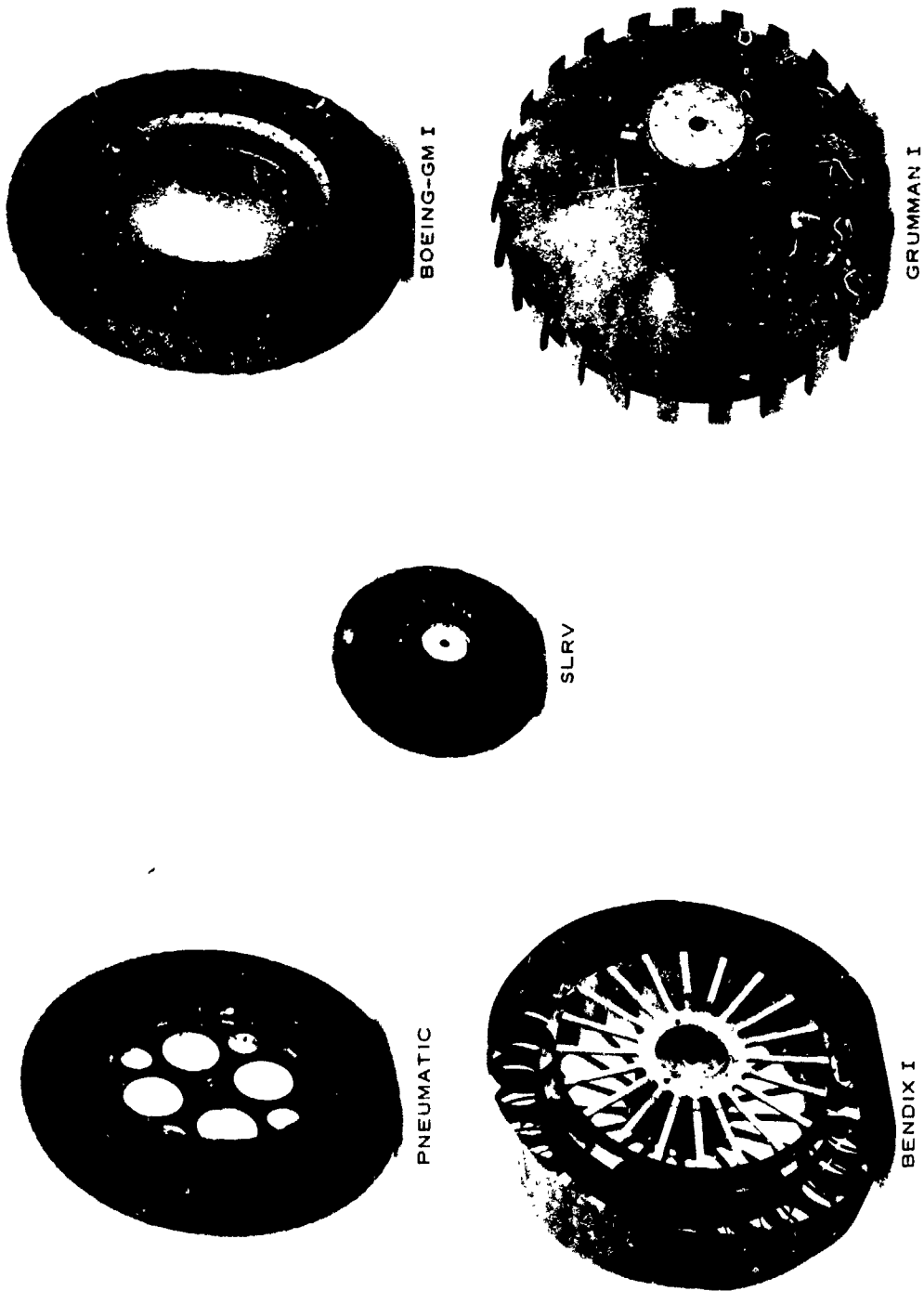


Fig. 5. Basic wheels tested in study of wheels for lunar vehicles

better accuracy than any other term examined. Also, a tire or wheel described within this prediction term need not have a section height. Data from tests of tires with small values of  $\delta/h$  (i.e. in the 0.01 to 0.10 range) are needed to determine this term's effectiveness for the small-deflection condition.

25.  $\frac{G}{W} \cdot A_c^{3/2}$ . Because the sponsor of the lunar studies expressed an interest in evaluating the effects of tire or wheel contact pressure on performance, a functional relation was developed that incorporated the parameter  $\frac{P}{W} = f\left(\frac{G}{W} \cdot A_c^{3/2}\right)$ , where  $A_c$  is hard-surface contact area.<sup>9</sup> Since the hard-surface print of a rigid wheel is a line and does not exhibit a measurable contact area, data for only the pneumatic tires are used in plate 5. The  $P/W$  versus  $\frac{G}{W} \cdot A_c^{3/2}$  relation appears better defined by the test data than corresponding relations of either of the two alternative prediction terms considered earlier (compare plate 5 with plates 3b and 4b). Thus, the effectiveness of  $\frac{G}{W} \cdot A_c^{3/2}$  in predicting pull/load is considered at least on a par with the two other alternative prediction terms for sand.

26. Prediction term  $\frac{G}{W} \cdot A_c^{3/2}$  possesses several disadvantages:
- a. Its form does not permit evaluation of the effects caused by changes in tire deflection, tire width, or tire diameter.
  - b. Rigid-wheel performance cannot be described by this term, and data are not available to determine its effectiveness in the  $\delta/h = 0.01$  to  $0.14$  range.
  - c. Measurement  $A_c$  varies as a function of a number of parameters-- $b$ ,  $d$ ,  $W$ ,  $\delta/h$  (in lieu of inflation pressure), carcass stiffness, etc.--and extensive listings of  $A_c$  for various tire loading conditions are not routinely supplied by tire manufacturers.

On the other hand, this prediction term can be profitably used if the user has available to him an accurate measurement of  $A_c$  (this can be obtained easily by coating the tire with a marking liquid and measuring

the print area produced on a flat, unyielding surface by the loaded, inflated tire).

27. Summation. Each alternative prediction term--  $\frac{G(b\delta)^{3/2}}{W}$   $\cdot \left(1 - \frac{\delta}{h}\right)^{-4}$ ,  $\frac{Gb\delta^2}{W} \cdot \left(1 - \frac{2\delta}{d}\right)^{-8}$ , and  $\frac{G}{W} \cdot A_c^{3/2}$ --predicts pneumatic tire performance in coarse-grained soils with useful accuracy; and the second term, in particular, predicts rigid-wheel performance quite well.

The basic prediction term  $\frac{G(b\delta)^{3/2}}{W} \cdot \frac{\delta}{h}$  predicts the performance of pneumatic tires with circular and rectangular cross sections and  $\delta/h$  values in the range normally used (and recommended) with better accuracy than any other prediction term examined; thus, this term is used in all remaining considerations of in-sand tire performance in this report.

#### Effects of velocity

28. The tests used to develop the foregoing relations were all conducted at speeds of 5 to 6 ft/sec. To determine whether wheel translational velocity  $V_w$  affects pneumatic tire performance in air-dry sand, constant 20 percent slip tests were conducted with two tires whose major dimensions scaled almost exactly 2:1--the 9.00-14, 2-PR and 4.00-7, 2-PR tires. Tests were made at one deflection condition ( $\delta/h = 0.25$ ) over a very broad range of wheel loads (44 to 1432 lb) and at design values of  $V_w$  from 0.8 to 18 ft/sec. A few programmed-increasing-slip tests also were conducted with the 9.00-14, 2-PR tire at  $V_w = 5$  ft/sec. The basic prediction term was used to consolidate the data. The value of pull coefficient  $P/W$  increased progressively as  $V_w$  increased, and the same central line could be used to describe the relation of  $P/W$  to the basic prediction term for both tires at three widely different values of  $V_w$ , i.e. 1.25, 5, and 13 ft/sec (plate 6). That  $P/W$  data for tires of considerably different linear measurements collapse to one central relation for three markedly different values of  $V_w$  suggests that the effects of velocity on tire performance do not scale according to tire size.

29. One means whereby the basic prediction term might be adjusted to account for the effects of wheel velocity while retaining the term's

dimensionless character is to relate wheel translational velocity  $V_w$  to some characteristic velocity associated with the test material (i.e. air-dry Yuma sand). A literature search revealed that shear wave velocity  $V_{sh}$  of an air-dry sand is logarithmically related to the vertical stress beneath the periphery of a rigid footing (termed confining pressure) when the footing is loaded transiently.<sup>10</sup> For the investigated cases in reference 10, confining pressure was calculated at a specified depth beneath the surface of the rigid footing through use of a Newmark chart. The conditions of the transient-load tests of a footing are approximated by loading the soil with a moving wheel; thus, estimates of shear wave velocities generated by wheels can be obtained by procedures similar to those in reference 10. Confining pressures were computed for the 4.00-7 and 9.00-14 tires for all test loads at a depth equal to their respective tire widths, by using known properties of the Yuma sand (dry density and void ratio were the principal soil properties), a rectangular approximation of tire contact area, and the procedures in reference 10. Corresponding values of shear wave velocity  $V_{sh}$  were computed, and the relation in fig. 6 was produced. This procedure was rather long and tedious; a very close approximation of confining

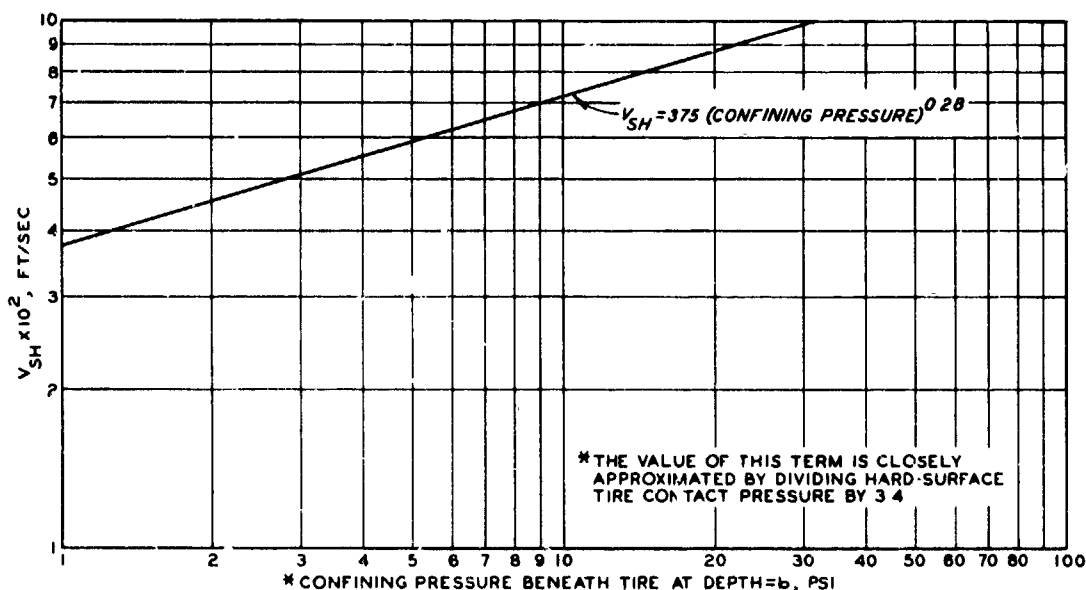


Fig. 6. Approximate relation of shear wave velocity to confining pressure for Yuma sand

pressure at a depth equal to the tire width was also obtained simply by dividing hard-surface contact pressure by 3.4 (note similarity of values of confining pressure by the two methods in table 4). A study of the relation between shear wave velocity  $V_{sh}$  and wheel translation velocity  $V_w$  relative to their influence on the pull coefficients of the

tires produced the dimensionless prediction term  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h} \cdot \left(\frac{150V_w}{V_{sh}}\right)^{1/2}$ . The ability of this term to delineate the effects of

wheel velocity is illustrated in plate 7, where the same central line shown in plate 2a describes the relation.

30. In summary, an estimate of shear wave velocity  $V_{sh}$  for air-dry Yuma sand was computed by the relation in fig. 6, where confining pressure at a depth equal to the tire width was estimated as hard-

surface contact pressure/3.4 ; and the prediction term  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h} \cdot \left(\frac{150V_w}{V_{sh}}\right)^{1/2}$  was shown to account quite effectively for the influence of

wheel translational velocity  $V_w$  on tire performance. This procedure lacks thorough grounding with respect to a detailed consideration of the types of forces that are introduced by changes in wheel velocity and that influence the tire performance results obtained. The prediction term in plate 7 shows promise of wide applicability; however, caution is advised in its use until a more rigorous evaluation of the effects of wheel velocity is made.

#### Effects of soil type

31. Fewer single-wheel tests have been conducted in air-dry mortar sand than in Yuma sand. Data taken from table 5 and presented in plate 8a are sufficient, however, to demonstrate that consistently smaller values of pull coefficient are developed by tires at 20 percent slip in mortar sand than in Yuma sand for corresponding values of the basic prediction term. Thus, parameter  $G$  apparently is not sufficient to account for the effect of both friction angle  $\phi$  and density  $\gamma$  (paragraph 11).

32. The relation between penetration resistance gradient  $G$  and relative density  $D_r$  for three air-dry, coarse-grained, essentially cohesionless soils (including the Yuma and mortar sands) has been studied at the WES.<sup>11</sup> For a given value of  $D_r$ , mortar and Yuma sands exhibit different values of  $G$ , as shown in fig. 7, developed from reference 11. Mortar sand  $G$  values were converted to corresponding Yuma sand  $G$  values by means of their relative density values, and then the new  $G$  values were used to plot the mortar sand test results (plate 8b). The central line of this plot is the same as that in plate 2a, indicating that the Yuma sand and mortar sand test results can be described by the same relation if relative density is used as a base. Use of the above-described technique to account for differences in soil type for air-dry, coarse-grained soils appears promising; however, caution is advised in applying it until further validation can be made.

#### Tires and Wheels in Clay

33. Single-wheel, multipass tests in laboratory near-saturated clay produced values of soil strength that remained essentially constant under tire traffic (paragraph 12). Accordingly, pull, torque, and towed force also remained near constant from pass to pass; whereas, sinkage increased after the first pass by an ever-decreasing amount, with second-pass sinkage usually only slightly larger than that on the first pass. Values of pull, torque, and towed force reported for each single-wheel test in clay are values averaged from all passes; sinkage values reported are those obtained on the first pass.

#### Basic prediction term

34. In a manner similar to that used for pneumatic tires in sand, dimensional analysis<sup>2</sup> combined three independent pi terms-- $C\ell^2/W$ ,  $b/d$ , and  $\delta/h$ --on the basis of their relation to four dependent pi terms-- $P'/W$ ,  $z/d$ ,  $M/Wr_a$ , and  $P'_T/W$ --to develop a single dimensionless term,  $\frac{Cbd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2}$ , referred to in reference 2 as the clay mobility number. The relations between this term and  $P'/W$ ,  $z/d$ ,  $M/Wr_a$ ,

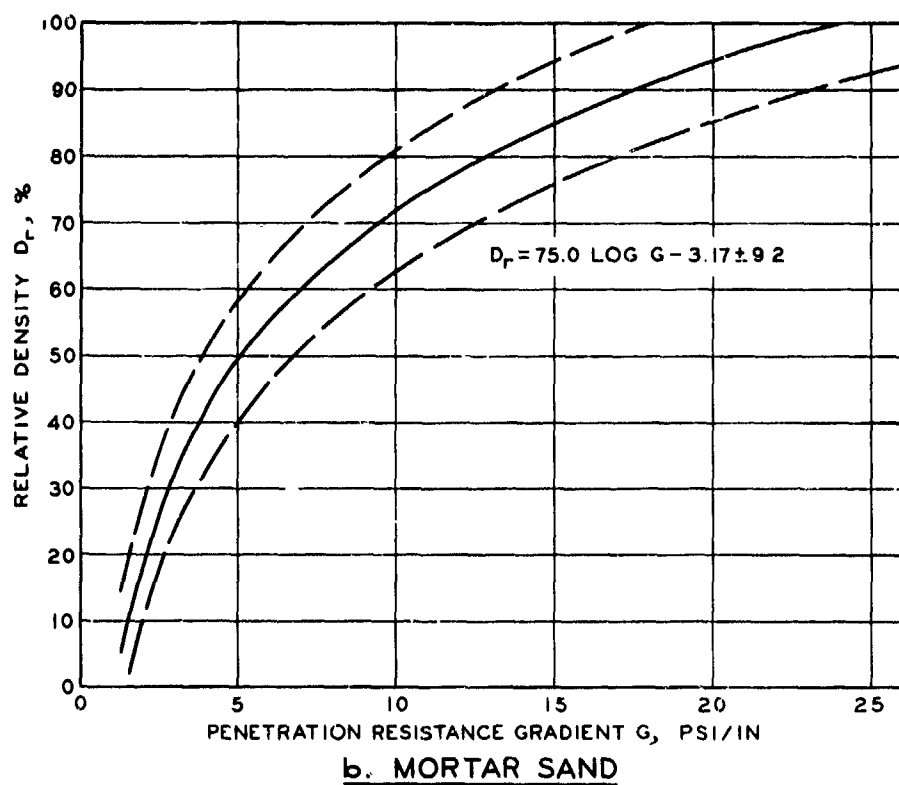
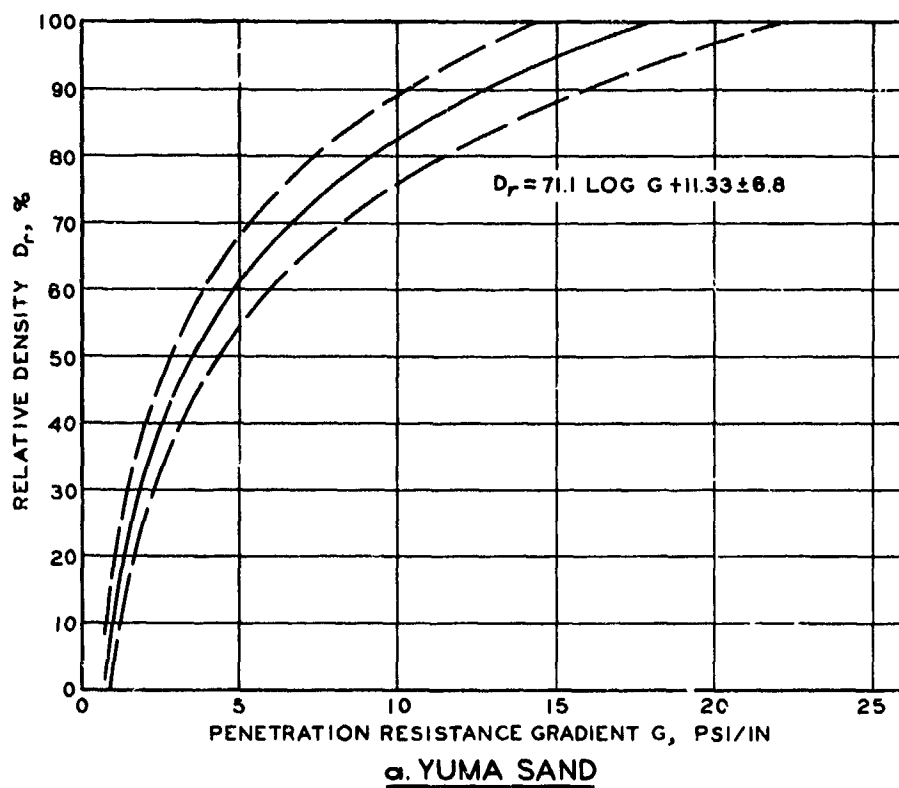


Fig. 7. Relation between relative density and penetration resistance gradient

and  $P'_T/W$ , respectively, are illustrated in plate 9. The data are from the same single-wheel laboratory tests that were examined in reference 2 for five of the six circular-cross-section tires; the two tests with the 1.75-26 bicycle tire were conducted after reference 2 was written. The clay mobility number is closely related to the four dimensionless performance terms. Note that scatter of the data increases for the relations of the clay mobility number to the pull, torque, and towed force coefficients as the values of the mobility number increase (and as value of wheel load decreases for a given combination of tire size and soil strength). The influence of the inertial force included as part of the  $P'$  and  $P'_T$  measurements on the overall values of  $P'/W$  and  $P'_T/W$  generally is most pronounced for light loads for tests conducted in clay (see Appendix A). Design load  $W$  is specified beside some of the outlying points in plate 9, demonstrating that a large part of the data scatter could be associated with very small wheel loads (the smallest tested for most of the tire size-deflection combinations included among those singled out in plate 9).

35. Results of single-wheel laboratory tests in saturated, fat clay were obtained for 12 tires, the same 11 pneumatic tires used herein in the study of tires and wheels in sand, plus a 6.00-16 solid rubber tire. The relations in plate 9 are repeated in plate 10 for data for six of the seven tires not included in plate 9. (Data from only towed tests of the 11.00-20, 12-PR tire are available; the relation of  $P'_T/W$  to the basic prediction term for clay is shown in a subsequent plate.) The same central line used in plate 9 to characterize the relation of the clay mobility number to the torque coefficient can also be used in plate 10. (Torque coefficient generally is less sensitive than the pull, sinkage, and towed force coefficients.) The rectangular-cross-section tires develop significantly smaller values of pull coefficient and generally slightly larger values of sinkage and towed force coefficients than the circular-cross-section tires. Data for the 6.00-16 solid rubber tire follow a third central tendency in all four relations.

36. The relations in plate 9 (for tires of diameter/width ratios in the 3 to 8 range) will coincide with those in plate 10 (for tires of

diameter/width ratios in the 1 to 2.5 range) if a properly formulated factor that reflects the influence of tire aspect ratio  $d/b$  is used in the clay mobility number. Multiplying  $\frac{Cbd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2}$  by  $\frac{1}{1 + (b/2d)}$  causes data for 10 of the 11 test tires to cluster about a single central line for each performance coefficient versus prediction term relation (plate 11). (The departure of data for the 6.00-16 solid rubber tire from each central relation is considered a minor deficiency.) For those tires for which  $P$  and  $P_T$  data are available (as opposed to  $P'$  and  $P'_T$  data for the 11 tires considered to this point), the prediction term  $\frac{Cbd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)}$  is very closely related to the pull and towed force coefficients (plate 12). The central lines in plate 12 indicate slightly smaller values of  $P/W$  and slightly larger values of  $P_T/W$  than those obtained in plate 11 for  $P'/W$  and  $P'_T/W$ , respectively, with these differences decreasing in magnitude as values of the prediction term decrease. This result agrees with findings in Appendix A and paragraph 13.

37. In summary, the term  $\frac{Cbd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)}$  predicts the four tire performance coefficients with useful accuracy for practically all pneumatic tire shapes now normally encountered. The form of this prediction term is simple and similar to that of the basic prediction term for sand,  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$ . Thus,  $\frac{Cbd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)}$  is referred to herein as the basic prediction term for clay.

#### Alternative prediction terms

38.  $\frac{Cbd}{W} \cdot \left(1 - \frac{\delta}{h}\right)^{-2} \cdot \frac{1}{1 + (b/2d)}$ . A procedure similar to that used in the development of the basic prediction term was used to relate functions of  $C$ ,  $b$ ,  $d$ ,  $W$ , and  $\left(1 - \frac{\delta}{h}\right)$  to the dimensionless performance terms.  $\left(1 - \frac{\delta}{h}\right)$  was chosen as the deflection term so that the performance of tires and wheels of a very broad range of deflection conditions could be predicted. As illustrated in plate 13a, this alternative prediction term correlates with pneumatic tire pull coefficient data

almost as well as the basic prediction term (plate 11), and collapses pull coefficient data for the 6.00-15 solid rubber tire to the central relation of the pneumatic tires much more effectively than does the basic prediction term. The one outlying data point for the solid rubber tire suggests that too large values of the pull coefficient may be predicted for tires with small deflection values as values of the alternative prediction term become large. (A similar trend was noted for the corresponding prediction term for sand in plate 3a and paragraph 21.) Plate 13b shows that very slightly smaller values of  $P/W$  than of  $P'/W$  (plate 13a) are obtained at corresponding values of the alternative prediction term.

$$39. \frac{C_b^{1/2} d^{3/2}}{W} \cdot \left(1 + \frac{4\delta}{d}\right)^4. \text{ This term was developed to allow the}$$

performance of tires and wheels in fine-grained soils to be predicted on the basis of  $C$ ,  $W$ ,  $\delta$ , and only two tire size measures, width  $b$  and diameter  $d$ . Comments made in paragraph 38 relative to the positioning of data in plate 13a apply almost directly to plate 14a, except the latter shows slightly more data scatter. This alternative term predicts the performance of pneumatic tires quite well, and predicts the performance of solid rubber tires ( $\delta/h$  values as small as 0.001) reasonably well for values of pull coefficient up to about 0.4. Again, slightly smaller values are obtained for  $P/W$  than for  $P'/W$ , all conditions being equal (plate 14b).

40.  $CA_c/W$ . The success achieved in incorporating hard-surface contact area  $A_c$  in a prediction term for sand (paragraphs 25 and 26) suggested a similar application for clay. A general relation exists between  $CA_c/W$  and pull coefficient, measured either as  $P/W$  or  $P'/W$  (plate 15), but the data scatter is excessive. Thus, use of  $CA_c/W$  to predict tire performance in fine-grained soils does not appear justified.

41. It is of interest to note that  $CA_c/W$  is the ratio of cone index to hard-surface contact pressure  $W/A_c$ . If the shear strength  $s$  of soil is taken as the dominant soil parameter that contributes to a tire's performance, and  $s$  is approximated from Coulomb by  $s = c + p \tan \phi$  ( $c$  = cohesion,  $p$  = contact pressure, and  $\phi$  = angle of

internal friction of the soil), then for purely cohesive soils, tire performance is independent of  $p$  (or  $W/A_c$  for tires), and for purely frictional soils, tire performance changes directly with  $p$ . Tire performance in cohesive soils is affected by tire size and shape; however, plate 15 illustrates that these effects are not delineated through use of simple contact area (and contact pressure). This plate, together with plate 5, generally support the hypothesis with regard to soil shear strength.

42. Summation. Both alternative prediction terms  $\frac{Cbd}{W}$   $\cdot \left(1 - \frac{\delta}{h}\right)^{-2} \cdot \frac{1}{1 + (b/2d)}$  and  $\frac{Cb^{1/2}d^{3/2}}{W} \cdot \left(1 + \frac{4\delta}{d}\right)^4$  predict pneumatic tire performance in clay with useful accuracy and predict solid tire performance with reasonably good accuracy; the scatter of the data increased as values of the prediction terms increased. Hard-surface contact area  $A_c$  appears not to delineate effectively the influence of tire geometry on performance. The basic prediction term  $\frac{Cbd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)}$  is more closely related to the tire performance coefficients than any other prediction term examined herein for pneumatic tires with  $\delta/h$  values generally used (and recommended) in off-road operations.

#### Effects of velocity

43. All of the foregoing relations for tires operating in clay were developed with data obtained in tests at values of wheel translational velocity  $V_w$  of 5 to 6 ft/sec. To determine whether  $V_w$  affects tire performance in saturated clay, tests were made with two essentially 2:1 scale-model tires (the 9.00-14, 2-PR and the 4.00-7, 2-PR) at one deflection condition ( $\delta/h = 0.25$ ), a wide range of wheel loads, and velocities that ranged from 0.5 to 18 ft/sec. The basic prediction term for clay was used to consolidate the data. Close examination of the data in plate 16a reveals that, for a given value of pull coefficient, the value of the basic prediction term generally decreased slightly with increasing values of  $V_w$  for each tire size. Also, values of the basic prediction term for the 9.00-14, 2-PR tire were

generally larger than those for the 4.00-7, 2-PR tire at corresponding values of pull coefficient.

44. One means whereby these trends can be diminished or removed is to increase the value of cone index as translational velocity increases, and to scale the size of this increase in inverse proportion to tire size. In a study at the WES of the effects of velocity on the penetration resistance of rigid cones of one shape (right circular, 30-deg apex angle) and a large range of sizes in three saturated, fine-grained

soils, the relation  $\frac{C_x}{C_s} = \left( \frac{V_x/d_x}{V_s/d_s} \right)^{0.092}$  was developed to describe the effects of viscosity on the penetration resistance of fat clay.<sup>12</sup> (Here,

$C_x$  is cone index obtained at any particular velocity  $V_x$  with a cone of diameter  $d_x$ ;  $C_s$  is synonymous with  $C$  and is cone index obtained at velocity  $V_s = 72$  in./min with a cone of diameter  $d_s = 0.798$  in.)

If width  $b$  for a tire is chosen to correspond to characteristic linear dimension  $d_x$  for a cone, and wheel translational velocity  $V_w$  is substituted for cone penetration velocity  $V_x$ , the equation  $C_x = C$

$\cdot \left( \frac{V_w/b}{V_s/d_s} \right)^{0.092}$  is obtained. Multiplying the basic prediction term

by  $\left( \frac{V_w/b}{V_s/d_s} \right)^{0.092}$  improves the relation in plate 16a considerably, but

produces prediction term values smaller than those in plate 12 by about 25 percent. This difference can be eliminated either by multiplying by 0.80 or using  $0.1V_w$  in the velocity term  $[(0.1)^{0.092} = 0.809]$ . The same central relation as that in plate 12 is produced when the basic

prediction term is multiplied by  $\left( \frac{0.1V_w/b}{V_s/d_s} \right)^{0.092}$  (plate 16b).

45. The collapse of the test data to a central relation indicates that use of  $\left( \frac{0.1V_w/b}{V_s/d_s} \right)^{0.092}$  to account for velocity effects is basically correct. Two very broad assumptions were made in applying this term--(a) tire width  $b$  is the characteristic linear dimension of the tire (likely this is nearly correct, at least for cases of tire sinkages

that are small relative to  $b$ , as would be expected for tires operating at high speed), and (b) soil penetration resistance changes with the translational velocity of a tire at 20 percent slip in a manner similar to its change with penetration velocity of a cone. Although plate 16b indicates general success in the use of  $\left(\frac{0.1V_w/b}{V_s/d_s}\right)^{0.092}$ , caution is advised in its use since the technique needed to account for the effects of velocity on tire performance obviously needs refinement.

#### Effects of soil type

46. WES single-wheel laboratory tire tests have been made in only one saturated, fine-grained clay. Very likely, tire performance is influenced by differences among values of several parameters for a variety of fine-grained soils; these effects will be studied in future tests.

#### Effects of tire surface and soil surface conditions

47. Four 6.00-16, 4-PR tires, each with a different type of outer surface (nondirectional tread, aggressive chevron tread, smooth with traction aid, and buffed smooth (i.e. no tread)) (fig. 8) were tested at a deflection of 0.35 (in most tests) in saturated, fat clay with three types of surface conditions (unflooded, flooded and undrained, and flooded and drained).<sup>13</sup> Since preparation of these types of soil surfaces often produced nonuniform soil strength profiles with depth, and since the soil layer very near the surface influenced tire performance most, cone index in the 0- to 1-in. layer was used to characterize soil strength. Pull remained unchanged through five passes in the unflooded soil, increased with each pass in the flooded and drained soil, and decreased with traffic in the flooded and undrained soil. First-pass pull performance for the flooded and drained and the flooded and undrained conditions were essentially the same. The magnitude of pull depended to some extent on the duration of the flooding; lowest pulls due to slipperiness were attained when the flooding period was brief and the soil strength high.

48. For a given wheel load, the value of loss of pull due to flooding, expressed as a percentage of the pull in the unflooded



a. 6.00-16, 4-PR tire with non-directional military tread



b. 6.00-16, 4-PR tire with aggressive chevron tread



c. 6.00-16, 4-PR smooth tire with traction aid



d. 6.00-16, 4-PR smooth tire

Fig. 8. Test tires used in study of effects of wet-surface conditions on tire performance

condition, was essentially a constant for each tread pattern, and took values of approximately 40, 50, 60, and 90 percent for the nondirectional, aggressive chevron, smooth with traction aid, and buffed smooth tires, respectively. In the unflooded soil, the tread pattern made a noticeable difference in performance (plate 17a). The tire equipped with traction aid developed the largest values of pull coefficient, the values developed by the smooth tire and the tire with aggressive chevron tread were about 15 percent smaller, and those produced by the tire with nondirectional tread were smaller by about 30 percent. The central relation of pull coefficient to the basic prediction term for the smooth 6.00-16, 4-PR tire tested in unflooded sections (plate 17a) was somewhat different from the central line in plate 11 for 11 smooth pneumatic tires (solid line in plates 17a and 17b). This difference resulted, at least in part, because an indicator of soil strength over the 0- to 6-in. layer was used for the relation in plate 11. Obviously, too, the difference between shapes of the two curves is an indication of the precision with which the relations in plate 11 can be applied to a particular tire-soil situation. Relative to the curve transferred from plate 11, only the smooth tire with traction aid developed significantly larger values of pull coefficient over an extended range of values of the basic prediction term.

49. In flooded soil, the treaded tires and the smooth tire with traction aid performed about equally well and considerably better than the smooth tire (plate 17b); however, all the tires performed far worse in the flooded conditions than the buffed-smooth tires tested routinely in unflooded test sections.

50. In summary, flooding a near-saturated fine-grained soil greatly reduces the pull performance of tires with four very different surfaces (plates 17a and 17b). Protrusions from a tire surface (whether integral tire tread or attached traction aid) appear to improve tire performance significantly in flooded soil test sections, largely because they "bite" through the weak soil surface to gain traction in stronger, underlying soil layers. For this environment, the type or shape of the protrusion used appears to influence performance only slightly. For the

unflooded soil surface condition, a smooth tire performed generally as well as or better than the two treaded tires, and the tire with traction aid performed better than the smooth tire only after values of the basic prediction term exceeded about 7. For this condition, soil strength and slipperiness were essentially constant with depth, so that penetrating the soil surface with tire protrusions did not influence pull performance as much as it did in the flooded test sections.

### PART III: VEHICLE VERSUS SINGLE-WHEEL PERFORMANCE

#### Limitations

51. Only the basic prediction terms for sand and for clay are considered in the remaining analyses in this report. Before any of the relations presented herein for tires tested singly in the laboratory are extrapolated to the prototype vehicle-field situation, cognizance must be taken of several major, largely uninvestigated factors that influence this operation.

#### Soil classes

52. The single-wheel tests were conducted on only two broad soil classes: (a) air-dry, almost purely frictional sand and (b) near-saturated, almost purely cohesive clay. Prediction terms that were developed differed basically according to these two soil classes. Thus, to this extent, soil classification is a needed independent parameter, and extrapolation of relations developed from the test data will be valid for any given soil only insofar as that soil's properties approximate those of one of the two soil classes tested.

53. The restriction above is not too severe, since the two tested soil classes represent a very broad spectrum of field environments that pose significant problems for wheeled vehicle mobility. The prediction term developed for sand can be used for soils that occur on sand beaches and in dune areas, and for predominantly sandy soils that are dry and loose, especially near the surface. The prediction term developed for clay can be used for wet, soft, fine-grained and clayey soils, e.g. rice paddies, marshes, tilled fields during the wet season, low-lying bottomlands, etc. Neither prediction term developed from tests in the laboratory will provide a good estimate of performance on fine-grained or clayey soils that are dry or only moist; however, vehicles generally perform much better in dry-to-moist soils than in those used in the laboratory test program. Thus, for design considerations, relations developed from laboratory tests in the two broad soil classes generally provide for the worst probable soil conditions.

#### Soil strength profiles

54. Prediction of field results by laboratory-developed relations is limited seriously by the fact that the laboratory relations are strictly valid only for soil strength profiles that are uniform with depth (near constant penetration resistance for clays, linearly increasing for sands). Layered or nonuniform soils have not yet been studied enough to understand and correlate the influences of soil strength discontinuities. Without doubt, layered or nonuniform soil strengths can markedly affect wheel performance, and some of the differences between laboratory and field test results stem from differences in soil profiles obtained in the two environments.

#### Tread pattern

55. The effect of tread pattern is a largely unevaluated tire parameter closely related to the problem of layered soil. Tire tread is known to be important when it allows the tire to obtain contact with a stronger soil layer. In all routine tests to date, tread was removed from the test tires to prevent tread effects being confounded with other, more basic tire parameters (size, shape, etc.). A very limited amount of test data was obtained in the study of pneumatic tire performance on clay with a slippery surface (paragraphs 47-50); sufficient data are not available, however, to evaluate tread pattern in a design analysis, even in a relative sense.

#### Translational velocity

56. Relations have been developed that appear to account for the influence on tire performance at 20 percent slip of wheel translational velocity over a relatively wide range of values (about 1 to 18 ft/sec) in sand and in clay (paragraphs 28-30 and 43-45, respectively). Further study is needed to develop accurate, quantitative descriptions of soil-wheel interactions in terms of effects classically used to describe the influence of velocity (i.e. in terms of viscous effects, inertial effects, etc.).

#### Wheel slip

57. For the single-wheel test data examined herein, three of the four performance parameters--pull, torque, and sinkage--were evaluated

at one slip level, 20 percent. For most of the test data, this resulted in sampling the performance parameters at 90 percent or more of their maximum values. The 20 percent slip level is considered a reasonable design basis because (a) slightly conservative predictions of attainable performance usually are desirable, and (b) for many situations, particularly in clay, the slight increase in pull obtained by operating at slip values larger than 20 percent is more than offset by associated penalties of excessive sinkage and reduced forward movement. An ability to predict tire performance at any of a wide range of slip values would improve the description of the towed condition, in particular, since this performance level occurs over a fairly wide range of negative slip values (about -1 to -15 percent), and different test techniques have been found to produce different values of towed force, all conditions being equal.<sup>14</sup>

#### Vehicle operating characteristics

58. Conventional, full-scale, wheeled vehicles possess several operating characteristics that usually cause their average wheel performance to be worse than that obtained for any one of their wheels tested singly. Among these characteristics are differential wheel slip (front to rear, or side to side, or both), change in wheel load due to dynamic weight transfer, steering forces, and differences in motion resistance caused by imperfectly tracking rear wheels. A detailed description of the mechanism of wheeled vehicle dynamic weight transfer has been formulated.<sup>15</sup> Test-proven, quantitative descriptions of the effects produced by each of the above-listed vehicle operating characteristics are largely lacking.

#### Summation

59. Relations have been developed from the single-wheel laboratory tests to predict tire performance for a very broad range of values of wheel load, soil strength, and tire size, shape, and deflection. Scant knowledge of the effects of several important soil and tire parameters (paragraphs 52-57) and of several vehicle operating characteristics (paragraph 58) causes problems in extrapolating the single-wheel laboratory relations to predict prototype wheeled vehicle performance in the field.

## Tests in Sand

### Extrapolating single-wheel, multipass relations to predict vehicle performance

60. Prediction of the performance of a pneumatic-tired vehicle with two or more wheels traveling in the same path imposes a requirement similar to the prediction of the performance of a single wheel on each of multiple passes in a single path. In either case, the performance of each wheel is influenced by the soil condition created by the preceding wheel or wheels. For air-dry Yuma sand, the value of  $G$  may either increase or decrease under the action of tire traffic, depending on several factors (initial soil strength, wheel load, tire size, etc.). Thus, use of the before-traffic measurement of  $G$  causes more scatter in relations involving multipass, single-wheel data than use of values of  $G$  measured just prior to each pass. This increase in scatter must be accepted as a necessary crudity, however, since it is not practical to measure soil strength just prior to the passage of each individual wheel of a vehicle.

61. Relations of the pull and towed force coefficients to the basic prediction term  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$  are demonstrated in plate 18 for all second-pass and third-pass conditions of single-wheel tests in which pull values were corrected for the effects of inertia. Scatter of the test data is relatively constant between passes, with the central lines indicating that values of  $P/W$  and of  $P_T/W$  are smaller for the third pass by a very small amount for all values of the basic prediction term. A comparison of results of pass one and pass two (plates 2 and 18) shows that values of  $P/W$  decreased considerably with traffic, whereas values of  $P_T/W$  showed very little change.

62. To simulate the performance of two- and three-axle wheeled vehicles, data from the multiple-pass tests in table 9 were combined as follows: (a) The pull (or towed force) coefficient for two- and three-axle vehicles was taken as the average of the corresponding coefficient for passes one and two, and for passes one, two, and three, respectively,

of the single wheel. (b) Values of  $W$  in the basic prediction term were taken as the average of wheel loads either for passes one and two, or for passes one, two, and three, respectively. (All other factors in the basic prediction term were constants, with  $G$  the before-traffic measurement.) Plate 19 demonstrates that this procedure produced very well-defined relations of the pull and towed force coefficients to the basic prediction term, and that each of these relations is effectively delineated by a single central curve. The curves in plate 19 are intended to simulate both two-axle and three-axle vehicle performance in the laboratory.

#### Laboratory tests of 4x4 vehicles

63. Three standard military vehicles equipped with treaded tires were tested at constant 20 percent slip in Yuma sand test sections that were prepared in the same manner as those for the single-wheel tests. The test vehicles were carefully steered in a straight line at low forward speed. Results of the tests are shown as discrete data points in plate 20. The smooth curve in plate 20 is the same as the curves in plates 19a and 19b, and represents very well the central tendency of the relation produced from the performance data of the three test vehicles.

#### Field tests of wheeled vehicles

64. Field tests have been conducted on coarse-grained soils in various parts of the world with a variety of military vehicles.<sup>16</sup> In nearly every case, most, if not all, of the factors discussed in paragraphs 52-58 were acting. Sand at the test sites usually was moist or even wet; drawbar-pull tests usually were not run at a controlled slip, but were made at several levels of pull with only the data relevant to the maximum attained pull recorded for each test; and no special provisions were made to control differential wheel slip, dynamic weight transfer, or steering forces. To effect even a first-order evaluation of the basic prediction term for sand, the following assumptions were made:

- a. The cohesive forces were negligible.
- b. An equivalent  $G$  can be computed from the 0- to 6-in. penetration resistance data recorded in the reference

(see Appendix A). This implies that the rate of increase of strength with depth (G) was nearly constant for a given field test to at least the 6-in. depth.

- c. The vehicles were loaded so that each tire carried an equal share of the load.

65. Maximum-drawbar-pull data from field tests with various 4x4 and 6x6 wheeled vehicles are recorded in table 12, and towed-test data in table 13.<sup>3</sup> The tests were conducted on dry-to-moist sands on various ocean and river beaches and dunes in the United States, and on beaches in the South Pacific and in France. The basic prediction term for sand consolidates all the maximum-drawbar-pull data to one relation and the towed data to another, so that a single central curve can be used to delineate each (plate 21). This is encouraging, since a wide variety of tire sizes, shapes, deflection conditions, tread patterns, loads, and coarse-grained soil conditions are represented. It indicates, also, that the assumptions listed in paragraph 64 provide a valid basis for grouping vehicle performance data.

66. In plate 22, the central curves from plates 19 and 21 are compared. For each relation, the field and laboratory curves have the same general shape, and consistently poorer performance was obtained in the vehicle field tests than in the single-wheel laboratory tests. The central lines established for vehicle performance in the field offer the basis for a tentative performance prediction system, and for design criteria for vehicles operating in dry-to-moist sands (plate 23). These curves can be used to forecast the mobility of existing vehicles or to select tires that will provide the desired degree of sand mobility for existing or proposed vehicles. Examples for applying these curves are presented in Appendix B.

#### Tests in Clay

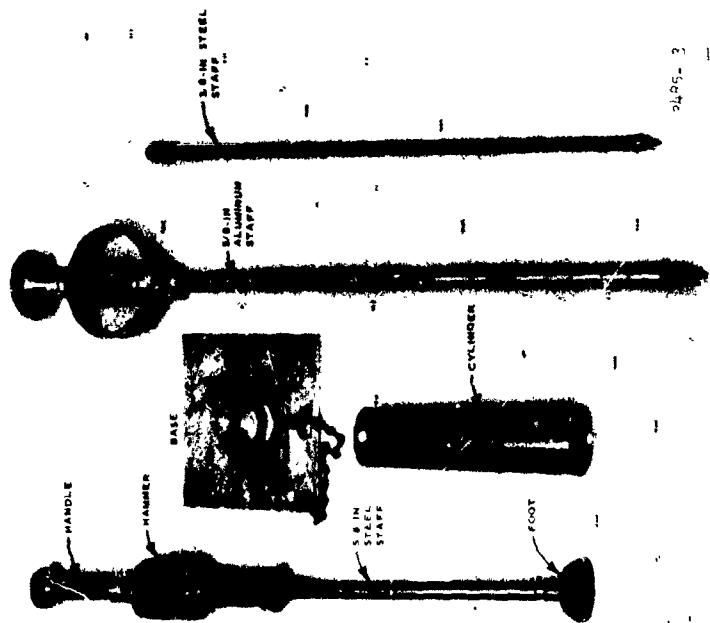
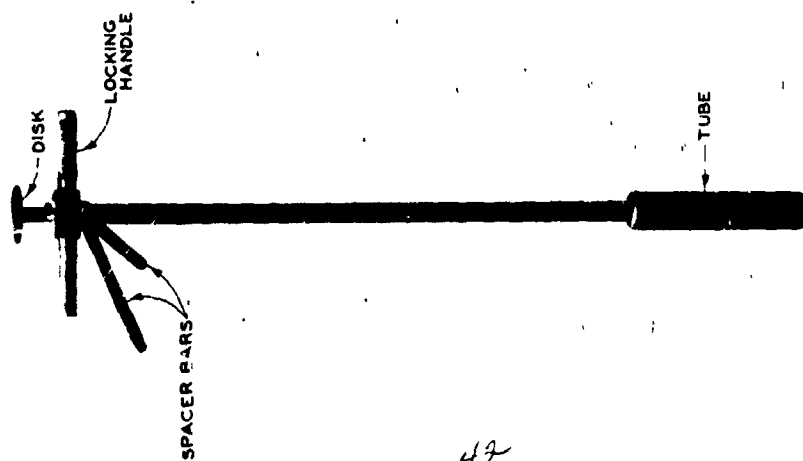
Extrapolating single-wheel  
multipass relations to  
predict vehicle performance

67. No vehicle tests have been conducted in the laboratory in clay because multipass, single-wheel tests showed that cone index, tire

pull, and torque remain essentially constant under tire traffic in the laboratory (paragraphs 12 and 33). If the strength characteristics of fine-grained soils encountered in the field are approximated by those of the laboratory clay, and if none of the factors discussed in paragraphs 52-58 degrade field vehicle performance, then the average tire performance of a vehicle should equal that obtained in single-wheel, multipass tests in the laboratory. Unfortunately, neither of these hypotheses is even roughly satisfied in typical vehicle operations in the field. All of the factors in paragraphs 52-58 do affect wheeled vehicle performance in fine-grained soils, so that poorer performance in the field is expected. Also, soil conditions encountered in the field are often anything but homogeneous, and the soil may either gain or lose strength under wheeled traffic. At least two options for characterizing in-the-field, fine-grained soil strength present themselves. First, the before-traffic soil condition described by the average value of cone index within a specified soil layer can be employed; i.e., identically the same technique that has been used in the laboratory can be applied to the field situation. A second technique that has been used for a number of years at the WES to describe the state of the soil for trafficability purposes (i.e. for repeated traffic, usually 50 passes, of vehicles in the field) involves an attempt to convert the before-traffic average cone index value to the value that predominates during the trafficability test. This is done by multiplying before-traffic average cone index by the dimensionless remolding index  $RI^*$  for the particular soil layer of interest to obtain the rating cone index  $RCI$ . Cone index measurements are made at the surface and at 1-in.-vertical increments to a depth of 4 in. before and after compaction. The ratio of the sum of cone index values obtained after compaction to the sum of those obtained

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\*  $RI$  is obtained by placing an undisturbed sample of the test soil, approximately 7 in. long and 1.9 in. in diameter, in a cylinder of approximately the same dimensions attached to a base plate, and subjecting the soil to 100 blows with a 2-1/2-lb hammer falling 12 in. (fig. 9). For very weak soils (cone index values of about 10 and under) the sample is enclosed, and the entire test instrument is dropped 25 times onto a rigid surface from a height of 6 in.



a. Trafficability sampler

b. Remolding equipment

c. Applying blows to remolding sample

Fig. 9. Obtaining remolding index for fine-grained soils

before compaction, expressed as a decimal, is the remolding index. No claim is made that this mechanical technique\* duplicates the action of a wheel in soil; it is emphasized, however, that RCI correlates more closely with parameters that describe trafficability test results than does any of a number of other soil parameters that have been investigated in the trafficability studies. In particular, RCI has been found very effective in collapsing to a single relation trafficability test results obtained in a wide variety of fine-grained soil types and strengths. Both average cone index and RCI, each measured in the 0- to 6-in. layer, are examined herein for their utility in describing soil strength for the one-pass, in-the-field, wheeled vehicle situation.

#### Field tests of wheeled vehicles

68. Unlike the laboratory tests, field tests usually were not run at a controlled slip, but were made at several levels of pull. Since the pull-slip curve for clay does not peak at 20 percent slip (fig. 3b), as it does for sand (fig. 3a), the influence of differential wheel slip should influence vehicle performance in clay less than it does in sand. The fact that wheel pull usually increases monotonically with slip (albeit the rate of increase in the range of positive slip values larger than about 15 percent is small) causes maximum pull to be attained when the wheel is making very little forward movement. Under these conditions, the wheel is performing near-zero useful work. Thus, a performance parameter that describes the work performed by the wheel is needed to select the slip level at which pull should be sampled. Work output index is a dimensionless number that indicates the vehicle's towing ability and is defined as follows:

$$\text{Work output index} = \frac{P}{W} \times \frac{\text{distance vehicle traveled}}{\text{distance wheels traveled}} = \frac{P}{W} (1 - \text{slip})$$

Wheel slip at which the maximum work output index occurs is termed optimum slip.

69. Data from field tests of five wheeled vehicles are presented

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\* See footnote on page 41.

in tables 14 and 15. These data were obtained from only two<sup>17,18</sup> of the many sources examined because only in these two references were sufficient pull and slip data reported to define with some assurance the value of maximum work output index, and hence optimum slip. Reference 17 and this report use values of  $P/W$  obtained at the slip value where a plot of work output index versus slip indicates maximum work output. Corresponding plots were made for those tests in reference 18 for which sufficient pull and slip data were available to define the maximum work output condition (fig. 10). Values of optimum slip from these two references fall in the 15 to 30 percent slip range (table 14),

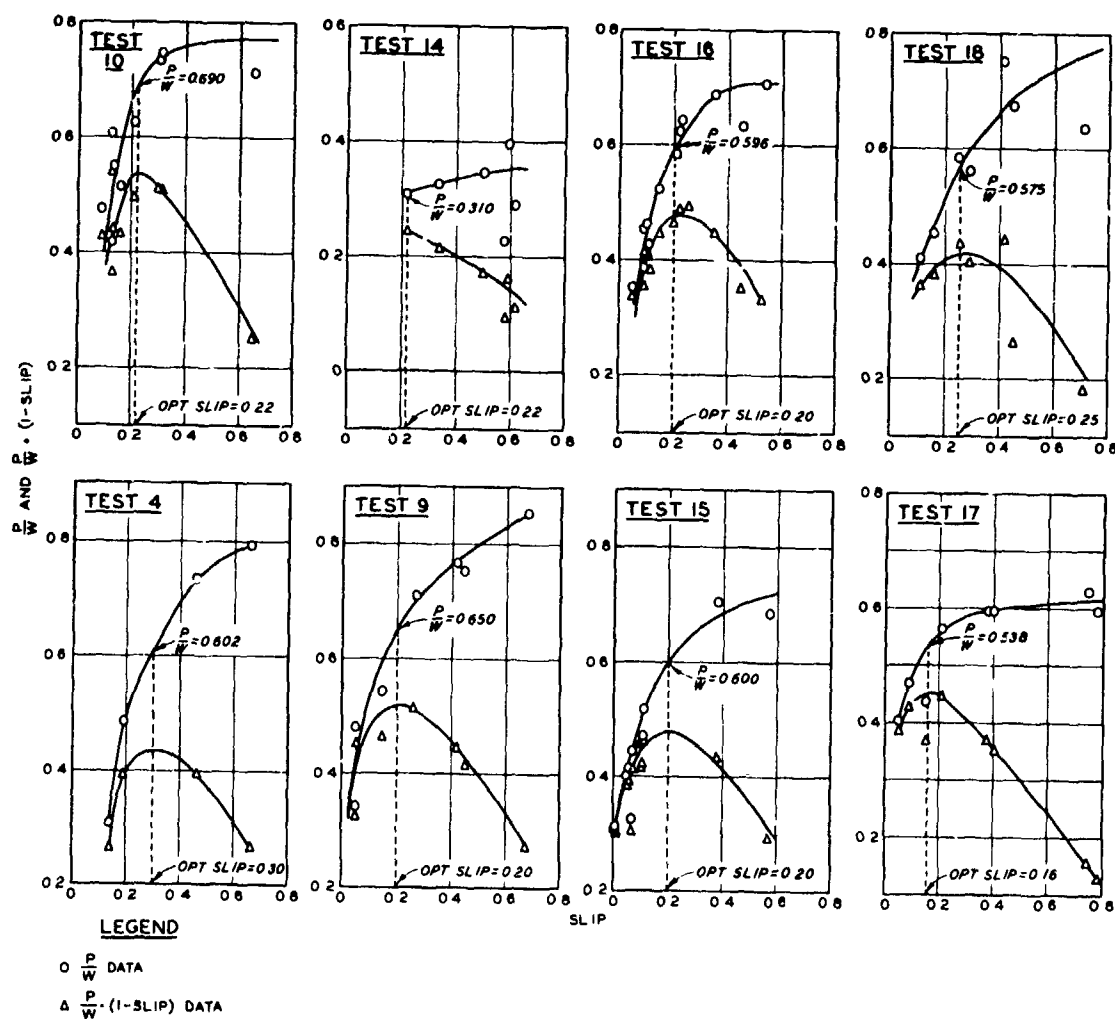


Fig. 10. Relations of  $\frac{P}{W}$  and  $\frac{P}{W} \cdot (1 - \text{slip})$  to slip

but average 20.5 percent and cluster closely about this value (standard deviation of 3.6 percent slip). Thus, data sampled at the 20 percent slip point in the laboratory single-wheel tests in clay can justifiably be compared with wheeled vehicle performance data sampled at the optimum slip level in field tests.

70. Values of towed force coefficient and pull coefficient at maximum work output obtained in the field tests of five wheeled vehicles correlate quite well with values of the basic prediction term for clay when either cone index or RCI in the 0- to 6-in. layer is used to characterize soil strength (plates 24 and 25, respectively). This is encouraging not only because a variety of vehicle configurations, wheel loads, and tire sizes, shapes, and deflection values are included among these data, but also because soil strength conditions from the field appear to have been adequately described in terms of either cone index or RCI. Before-traffic values of cone index at 1-in. vertical increments in the 0- to 6-in. layer often differed by at least a factor of 2 for a given cone index profile, as shown in tables 14 and 15.

71. Central lines used to describe the laboratory and field test results are compared in plate 26 for soil strength described by cone index. Values of pull coefficient increase much more rapidly for the field than for the laboratory data for values of the basic prediction term up to about 6.5, and much more slowly thereafter. The Y-axis asymptote of the equation used to describe the field data agrees with WES experience that wheeled vehicles in the field rarely attain P/W values larger than 0.8 at optimum slip in wet, fine-grained soils. The central lines of the towed force coefficient versus basic prediction term relation for field and laboratory have the same shapes, but the curve for the field data is located above and to the right of the laboratory curve.

72. Average wheel performance of vehicles in the field was expected to be different (and generally poorer) than single-wheel performance in the laboratory because of the factors presented in paragraphs 46-50 and 52-58. Probably most influential of these in-the-field factors were differences in soil types, irregularity of soil strength profiles (extremely so in some cases), slippery soil surfaces, and

changes in soil strength caused by wheeled traffic. Also, large values of the basic prediction term were usually produced in the laboratory with moderate values of  $C$  (none larger than 68) and very small values of  $W$  (as small as 100 lb). Corresponding values in the field were obtained with very large values of  $C$  (over 100 in some cases) and moderate values of  $W$  (none smaller than about 1800 lb). The laboratory condition--moderate  $C$ , very small  $W$ --appears either to produce better tire flotation or to utilize soil strength better than the field condition.

73. The comparison of central relations from laboratory and field is not as straightforward for soil strength measured by RCI as it is for soil strength measured by cone index. This occurs, first, because RCI measurements were not routinely taken in the laboratory single-wheel program. To get an indication of the values that would have been obtained, cone index and RI were measured in the 0- to 6-in. layer at three locations in each of three representative test sections of the laboratory clay (a low-, an intermediate-, and a high-strength section), and RCI values were computed. The following values were obtained:

Location No.	Low-Strength Test Section			Intermediate-Strength Test Section			High-Strength Test Section		
	1	2	3	1	2	3	1	2	3
Cone index	22.7	22.1	17.9	33.9	32.6	32.9	67.9	76.9	71.1
RI	0.83	0.95	0.86	0.93	0.92	0.98	0.93	0.87	0.84
RCI	18.8	21.0	15.4	31.5	30.0	32.2	63.1	66.9	59.8

The average of the nine RI values is 0.90, and there appears no rational correlation between RI and cone index. It was reasonable, then, to multiply the abscissa term of the central lines for the laboratory data in plate 12 by 0.90 to approximate the relations expected if RCI measurements had been available. These adjusted central lines are shown in plate 27, together with the central lines obtained for the field data (from plate 25). The relative shapes of laboratory and field curves for the  $P/W$  versus basic prediction term relation in plate 27 are similar to those obtained when soil strength is described by cone index

(plate 26); in plate 27, however, the field curve lies above the laboratory curve for X-axis values from about 3.1 to 6.3. Vehicle operating characteristics are thought to cause worse overall vehicle performance than that expected of each of its wheels tested singly (paragraph 58), which implies that RI for the field tests reduced the soil strength measurement (RCI) too much for values of  $\frac{(RCI)bd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + b/2d}$  less than about 6.3. (Values of RI in this range of prediction term values averaged 0.69.) The central lines of the towed force coefficient versus basic prediction term relation for the field and laboratory data in plate 27 are aligned in a fashion similar to corresponding curves based on cone index in plate 26.

74. On the basis of field and field-versus-laboratory data presented herein, no clear-cut decision can be made regarding which of the soil strength descriptors--average cone index or RCI--should be used in predicting one-pass wheeled vehicle performance. Slightly less data scatter was achieved using RCI (see plates 24 and 25), but the central lines of the laboratory and field data for the pull coefficient versus basic prediction term relation indicate that RI affected RCI values obtained for the laboratory and field test soils differently (plate 27). A reasonable test of the adequacy of RI to indicate change in strength for one pass of a wheeled vehicle would involve comparing RI values with the ratio  $\frac{\text{after-one-vehicle-pass average 0- to 6-in. cone index}}{\text{before-traffic 0- to 6-in. cone index}}$  for a number of combinations of soil type, soil strength, wheel load, vehicle configuration, tire size, tire shape, and tire deflection. Very likely, a 1-to-1 correlation between these two terms would be obtained only after some modification is applied to the process for obtaining RI. (RI was developed for the multipass situation; see paragraph 67.) Since no after-first-pass cone index measurements were taken for any of the field tests reported herein, comparison of RCI with after-first-pass average cone index must await further testing.

75. At this point, then, the "problem" of choosing between cone index and RCI is somewhat moot, since each of these measurements was shown to correlate quite well with major parameters that describe

one-pass wheeled vehicle performance. Because WES experience has shown that RCI effectively describes soil strength on a common basis for a wide variety of types and consistencies of fine-grained soils, relations developed in the remainder of this report for vehicles operating in fine-grained soils use RCI for the soil strength measurement. The central relations established for field vehicle performance in wet, fine-grained soils are presented in plate 28. These curves are suggested for use in a tentative performance prediction and/or vehicle design system; examples for applying them are presented in Appendix B.

#### PART IV: DESIGN CRITERIA

76. The following relations were determined by using the basic prediction terms for sand and clay  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$  and  $\frac{Cb_d}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)}$ , respectively, and the equations used to characterize near-maximum-pull data obtained for vehicles in the field in sand and clay (plates 23 and 28, respectively). Similar relations would be obtained if the alternate prediction terms were used.

##### Tires for Vehicles Operating in Sand

###### Optimum load

77. Consider the relation for near-maximum pull/load from plate 23, i.e.

$$\frac{P}{W} = \frac{\alpha - 5.50}{1.92\alpha + 37.20}, \text{ where } \alpha = \frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h} \quad (1)$$

or

$$\frac{P}{W} = \frac{\frac{k_1}{W} - 5.50}{1.92 \frac{k_1}{W} + 37.20}, \text{ where } k_1 = G(bd)^{3/2} \cdot \frac{\delta}{h} = \alpha W$$

$$\frac{P}{W} = \frac{k_1 - 5.50W}{1.92k_1 + 37.20W}$$

So

$$P = \frac{k_1 W - 5.50W^2}{1.92k_1 + 37.20W} \quad (2)$$

If there is an optimum load, then a plot of pull versus load will exhibit a peak and  $dP/dW$  at that point will equal 0.

$$\frac{dP}{dW} = \frac{(1.92k_1 + 37.20W)(k_1 - 11.00W) - (k_1 W - 5.50W^2)(37.20)}{(1.92k_1 + 37.20W)^2} = 0$$

or

$$1.92k_1^2 - 21.12k_1W + 37.20k_1W - 409.20W^2 - 37.20k_1W + 204.60W^2 = 0$$

Then

$$-204.60W^2 - 21.12k_1W + 1.92k_1^2 = 0$$

and

$$\begin{aligned} W_{\text{opt}} &= \frac{21.12k_1 \pm \sqrt{(21.12k_1)^2 - 4(-204.60)(1.92k_1^2)}}{2(-204.60)} \\ &= \frac{21.12k_1 - 44.92k_1}{-409.20} = \frac{-23.80k_1}{-409.20} = 0.0582k_1 \end{aligned} \quad (3)$$

From equation 2:

$$\begin{aligned} P_{\text{opt}} &= \frac{k_1(0.0582k_1) - 5.50(0.0582k_1)^2}{1.92k_1 + 37.20(0.0582k_1)} \\ &= \frac{0.0582k_1^2 - 0.0186k_1^2}{1.92k_1 + 2.165k_1} = 0.00969k_1 \end{aligned} \quad (4)$$

and

$$\frac{P_{\text{opt}}}{W_{\text{opt}}} = \frac{0.00969k_1}{0.0582k_1} = 0.166 \quad (5)$$

78. Thus, there are unique values of optimum load, optimum pull, and optimum pull/optimum load (equations 3, 4, and 5, respectively) for each particular sand-pneumatic tire situation. The ratio  $P_{\text{opt}}/W_{\text{opt}}$  should not be confused with pull coefficient  $P/W$  used to characterize near-maximum wheel pull performance in all considerations prior to paragraph 77. A particular value of  $P/W$  is obtained at each particular value of the basic prediction term, and values larger than 0.166 obviously are possible (plate 23). However, an optimum (or absolute maximum) pull is obtained for one particular value of load ( $W_{\text{opt}}$ ) at one level of pull/load (i.e.  $P_{\text{opt}}/W_{\text{opt}} = 0.166$ , equation 5) for all tires in sand (plate 29).

79. The relations developed in paragraph 77 are illustrated in plate 29 for one particular combination of tire size and deflection and

several values of penetration resistance gradient  $G$ . It will be noted that the shape of each curve is parabolic, and that a line drawn through the origin at a slope  $P/W = 0.166$  passes through the maximum value of  $P$  for each curve. Also, the values of  $P_{cpt}$  increase directly with increasing values of  $G$ , and the absolute value of  $P$  decreases as the value of  $P/W$  either increases or decreases from 0.166. Thus, the values of  $P/W$  larger than 0.166 in plate 23 are necessarily associated with smaller loads than those required to produce optimum pull ( $P/W$ 's  $> 0.166$  fall to the left of  $P/W = 0.166$  in plate 29). Equation 1 indicates that increasing the value of  $\alpha$  to a very large number (as occurs when the value of  $W$  becomes smaller,  $G$  becomes larger, etc.) causes the  $P/W$  value to approach a limit of  $1/1.92$ , or 0.521. It is of interest to note that 0.521 is the tangent of 27.5 deg, a value which is fairly representative of the angle of internal friction of many natural dry-to-moist sands.

#### Immobilization load

80. For most practical situations, the extreme load of interest is not a very light load, but the maximum load that a particular tire can transport. Immobilization load  $W_I$ , or the minimum load needed to cause zero pull, is computed from equation 1 by determining the load

that causes  $\alpha - 5.50$  to equal zero. Then, with  $k_1 = \frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$ ,

$W_I = k_1/5.50$  (from the relation  $P/W = \frac{k_1 - 5.50W_I}{1.92k_1 + 37.20W_I} = 0$  for the

immobilization condition). Since  $W_{opt} = 0.0582k_1$  (from equation 3), the ratio  $W_{opt}/W_I = 0.0582k_1/(k_1 \div 5.50) = 0.32$ , a constant. Thus for any particular tire-sand situation, immobilization occurs at a load approximately  $1/0.32$  or 3.1 times larger than the optimum load. The immobilization condition is an extremely important consideration in the design of tires for off-road use. In fact, running gear configurations for wheeled vehicles designed to operate off-road should be chosen primarily on the basis of an acceptable minimum soil strength  $G$  and the requirements imposed on  $b$ ,  $d$ , and  $\delta/h$  by the immobilization condition for that value of  $G$ .

## Effect of tire size and deflection on wheel pull

81. Effect of tire width and diameter. Values of pull coefficient (plate 23) and optimum pull, optimum load, and immobilization load (plate 29) all increase directly with increasing values of the basic prediction term. In this term, tire width  $b$  and diameter  $d$  each are raised to the same power, indicating that width and diameter affect tire performance equally. Whether to increase width or to increase diameter to improve tire performance must be decided from considerations relevant to each particular vehicle running gear design, e.g. horizontal and vertical space limitations, tire stability requirements, etc.

82. Effect of tire deflection. In the basic prediction term, deflection  $\delta/h$  has an exponent of 1, indicating that the same relative increase in the value of deflection (say doubling its values) will increase the value of the prediction term by a substantially smaller amount than a corresponding relative increase in either width or diameter ( $2^{3/2} = 2.83$ , for instance). Physically increasing either tire width or tire diameter costs money, while increasing tire deflection (by decreasing inflation pressure) costs nothing, at least within that range of values of deflection where a particular tire can operate effectively. Thus, it is clear that for very soft soil conditions, a tire should be designed for and operated at the largest values of deflection practicable.

### Tires for Vehicles Operating in Clay

#### Optimum load

83. Consider the relation for near-maximum pull/load from plate 28.

$$\frac{P}{W} = \frac{\beta_2 - 2.59}{1.25\beta_2 - 1.19}, \text{ where } \beta_2 = \frac{(RCI)bd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)} \quad (6)$$

or

$$\frac{P}{W} = \frac{k_2/W - 2.59}{(1.25k_2/W) - 1.19}, \text{ where } k_2 = (RCI)bd \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)} = \beta_2 W$$

So

$$P = \frac{k_2 W - 2.59 W^2}{1.25 k_2 - 1.19 W} \quad (7)$$

Solving for  $dP/dW = 0$  in terms of  $k_2$  and  $W$  yields

$$3.08 W^2 - 6.48 k_2 W + 1.25 k_2^2 = 0$$

and

$$W_{opt} = 0.211 k_2 \quad (8)$$

From equation 7:

$$P_{opt} = 0.096 k_2 \quad (9)$$

and

$$\frac{P_{opt}}{W_{opt}} = 0.455 \quad (10)$$

The relations developed above are illustrated in plate 30 for one particular tire size-deflection combination and a range of values of RCI. Maximum absolute values of pull are attained at  $P/W = 0.455$ ; these values increase directly with increasing values of RCI. Larger values of  $P/W$  are obtained in the relation in plate 28, but the decreasing values of load associated with values of  $P/W$  larger than 0.455 cause values of absolute pull to decrease from the maximum at  $P/W = 0.455$ . Equation 6 indicates that very large values of  $\beta_2$  (as would be produced by very small values of load) cause the value of  $P/W$  to approach a limit of  $1/1.25 = 0.80$ . It is interesting to note that the upper limits of wheel pull performance in clay are much larger than those in sand in terms of both  $P_{opt}/W_{opt}$  and of maximum  $P/W$  (0.455 versus 0.166, and 0.300 versus 0.521, respectively).

#### Immobilization load

$$\begin{aligned} 84. \text{ From } \frac{P}{W} = \frac{(k_2/W_I) - 2.59}{(1.25 k_2/W_I) - 1.19} = 0, \quad W_I = k_2/2.59, \text{ where } k_2 \\ = (RCI)bd \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)}. \text{ The ratio } \frac{W_{opt}}{W_I} = \frac{0.211 k_2}{k_2/2.59} = 0.55, \text{ a} \end{aligned}$$

constant. Thus, for any particular tire-clay situation, immobilization occurs at a load approximately  $1/0.55 = 1.8$  times larger than the optimum load.

#### Effect of tire size and deflection on wheel pull

85. Effect of tire width and diameter. Wheel pull performance increases directly with increasing values of the basic prediction term in terms of  $P/W$  (plate 28) and in terms of  $P_{opt}$ ,  $W_{opt}$ , and  $W_I$  (plate 30). Values of this term are influenced more by changes in the value of diameter than by changes in the value of width because of the factor  $\frac{1}{1 + (b/2d)}$ . For example, doubling the value of  $d$  increases the value of the basic prediction term by a factor of 2.4, whereas doubling the value of  $b$  increases the value by a factor of 1.5. Halving the value of  $d$  reduces the prediction term by 62 percent, whereas halving  $b$  reduces it by 40 percent. The greater influence of  $d$  results, of course, because  $\frac{2bd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)} = \frac{C}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{2bd}{2d + b}$ . How changes in the values of  $b$  and  $d$  influence the value of  $2bd^2/(2d + b)$  is shown in fig. 11, where  $2bd^2/(2d + b) = k$  for initial values of  $d = 1.0$  and  $b = 1.0$ . Doubling and halving the tire diameter and width are rather drastic alterations, of course; but even relatively small changes in the value of diameter influence the value of  $2bd^2/(2d + b)$  (and the basic prediction term) significantly more than corresponding changes in width, as shown in fig. 11.

86. Effect of tire deflection. The basic prediction term for clay is influenced by changes in deflection in a manner similar to, but less pronounced than, that caused by changes in the value of width  $b$  (e.g. halving deflection reduces the term by 30 percent; doubling deflection multiplies it by 1.4). Halving  $b$  reduces the term's value by 40 to 50 percent; doubling  $b$  multiplies it by 1.5 to 1.9, for  $b/d$  values initially in the 1/1 to 1/10 range. Changes in deflection influence the value of the prediction term significantly less than corresponding relative changes in the value of diameter  $d$ . Again, increasing the value of either width or diameter costs money; increasing the value

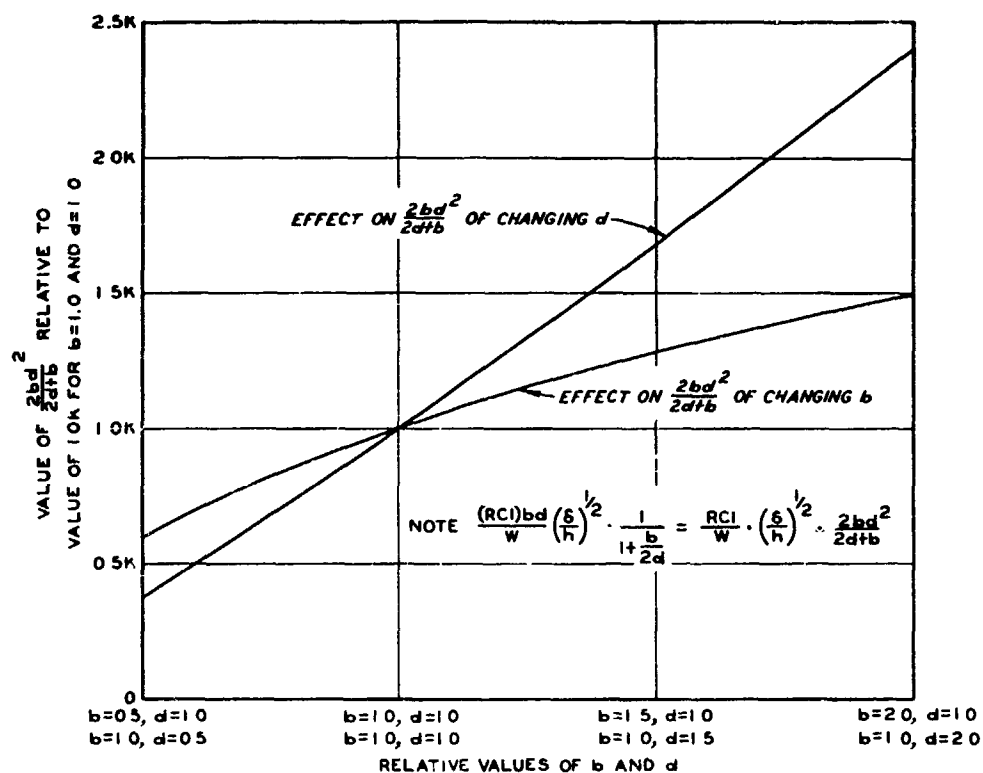


Fig. 1. Effects on  $\frac{2bd^2}{2d+b}$  caused by changing the values of  $b$  and  $d$

of deflection costs nothing (within the range of deflection values where a tire can operate effectively). Noteworthy, too, is the fact that changes in values of deflection influence tire performance in clay significantly less than corresponding changes in sand.

#### Summation

87. The relations discussed in paragraphs 76-86 are based on laboratory-established single-wheel prediction terms extrapolated to describe in-the-field, full-scale wheeled vehicle performance. The accuracy expected in applications of these relations to field situations is of the order indicated by the scatter bands in plates 21 and 24 for carefully conducted field tests. Considerably more testing and analysis are needed to describe the effects on tire performance of the many

factors not adequately quantified (primarily those in paragraphs 52-58). Nevertheless, the relations in plates 23, 28, 29, and 30 and in paragraphs 76-86 provide a reasonable base for predicting the performance of wheeled vehicles in the field and for selecting tire sizes, shapes, and deflections to satisfy particular wheeled vehicle-soil condition requirements in the field. Several examples of this type of application are presented in Appendix B.

## PART V: CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

58. The foregoing analysis is considered adequate basis for the following conclusions:

- a. The performance of single pneumatic tires of either circular or rectangular cross sections operating either in air-dry to moist sand or in near-saturated clay at the towed and near-maximum-pull conditions (taken as the 20 percent slip point in all laboratory tests) depends primarily on soil strength, wheel load, and tire size, shape, and deflection (with wheel translational velocity held constant) (paragraphs 6 and 7).
- b. One basic dimensionless prediction term for pneumatic tires operating in sand,  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$ , and another for pneumatic tires in clay,  $\frac{Cbd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)}$ , are demonstrated to predict in-soil, single-wheel, pneumatic tire performance (for tires at 0.15 to 0.35 deflection in sand and 0.08 to 0.45 deflection in clay) with better accuracy than any other prediction terms examined herein (paragraphs 17-27 and 34-42, and plates 1-2 and 11-12, respectively).
- c. Alternative prediction terms  $\frac{G(bd)^{3/2}}{W} \cdot \left(1 - \frac{\delta}{h}\right)^{-4}$  for tires in sand and  $\frac{Cbd}{W} \cdot \left(1 - \frac{\delta}{h}\right)^{-2} \cdot \frac{1}{1 + (b/2d)}$  for tires in clay predict single-wheel pneumatic tire pull performance with only slightly less precision than the basic prediction terms (compare plate 3 with plates 1a and 2a, and plate 13 with plates 11a and 12a, respectively). Also, these two alternative terms predict the pull performance of tires of very small deflection ( $\delta/h$

values of, say, 0.03 and smaller) much more accurately than do the basic prediction terms (paragraphs 21 and 38, respectively).

- d. Alternative prediction terms  $\frac{Gb d^2}{W} \cdot \left(1 - \frac{2\delta}{d}\right)^{-8}$  for tires in sand and  $\frac{Cb^{1/2} d^{3/2}}{W} \cdot \left(1 + \frac{4\delta}{d}\right)^4$  for tires in clay eliminate one tire dimension (section height  $h$ ) included in the terms in b and c above. They predict tire pull performance for pneumatic tires of conventional tire deflection values almost as well as their corresponding alternative prediction terms in c above, and predict the pull performance of tires of very small deflection approximately on a par with the alternative terms in c (paragraphs 23-24 and 39, and plates 4 and 14, respectively).
- e. Hard-surface contact area  $A_c$  can be incorporated in a dimensionless term  $\frac{G}{W} \cdot A_c^{3/2}$  useful for predicting tire performance in sand with slightly better accuracy than the alternative prediction terms for sand in c and d above (paragraphs 25-26 and plate 5).  $A_c$  appears to delineate the effects of tire geometry on pneumatic tire pull performance in clay less effectively than in sand (paragraphs 40-41 and plate 15).
- f. Increasing wheel translational velocity  $V_w$  (in the <1 to 18 ft/sec range) increases the pull coefficients in both sand and clay. In sand, this effect appears to be independent of tire size; in clay, the effect decreases as tire size increases. Multiplying the basic prediction terms by the empirically developed dimensionless terms  $\left(\frac{150V_w}{V_{sh}}\right)^{1/2}$  and  $\left(\frac{0.1V_w/b}{V_s/d_s}\right)^{0.092}$  for sand and clay, respectively, effectively collapses pull coefficient data to one central line for a broad range of values of  $V_w$  (paragraphs 28-30 and 43-45, and plates 6-7 and 16, respectively).

- g. The central relation of the basic prediction term for pneumatic tires in air-dry mortar sand can be adjusted to the same relation obtained for tires in air-dry Yuma sand by adjusting mortar sand values of penetration resistance  $G$  to Yuma sand  $G$  values on the basis of relative density (paragraphs 31-32, plate 8). No analysis was made relative to the effects of soil type on tire performance in fine-grained soils.
- h. Flooding the surface of a near-saturated, fine-grained soil test section reduces the pull coefficient drastically. Smooth tire performance is degraded most by flooding; whereas tires with tread or traction aid (rubber or steel cleats) perform about equally well at a level well above that of the smooth tire. Type of tread has more influence on the pull coefficient for the unflooded than for the flooded condition, but only a tire with traction aid performs significantly better than a smooth tire in an unflooded environment (paragraphs 47-50, and plate 17).
- i. Single-wheel pneumatic tire performance on second and third passes in sand is related to  $\frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$ , although the relation is not the same as that for the first pass. Laboratory tests demonstrated that in-sand, one-pass 4x4 vehicle pull performance can be predicted on the basis of the single-wheel, multipass relations (paragraphs 60-63 and plates 18-20). Soil strength and tire performance (except for sinkage) are essentially unaffected by traffic in the near-saturated laboratory clay; therefore, for this type of soil, nondimensional single-wheel performance can be equated directly to vehicle performance (paragraph 67).
- j. The basic prediction terms adequately collapse wheeled-vehicle field performance data for sand and clay to

relations similar to those obtained for single wheels in the laboratory (paragraphs 64-66 and 67-75, and plates 21-23 and 24-28, respectively). Where direct comparisons could be made, it was found that wheeled vehicles performed consistently worse in the field than single wheels performed in the laboratory, primarily because of the factors discussed in paragraphs 52-58.

- k. Major wheeled vehicle performance parameters correlate with the basic prediction term for clay (i.e. for fine-grained soils) about equally well when either cone index  $C$  or rating cone index  $RCI$  is used for the soil strength parameter (paragraphs 67-75 and plates 24 and 25).  $RCI$  is chosen as the parameter presently recommended for field applications because WES experience is that  $RCI$  effectively describes soil strength on a common basis for a wide variety of fine-grained soil types and consistencies.
- l. Optimum pull (i.e. absolute maximum pull), optimum load, and immobilization load can be computed on the basis of equations relating pull/load to the basic prediction terms for sand and for clay (paragraphs 77-80 and 83-84, and plates 29 and 30, respectively).
- m. Tire width and diameter influence tire performance in sand equally, but diameter has somewhat greater influence than width for tires in clay. Tire deflection  $\delta/h$  has less influence than either width or diameter on tire performance in either sand or clay. However, increases in deflection value can improve tire performance significantly, and this increase costs far less than corresponding relative increases in either width or diameter (paragraphs 81-82 and 85-86).

#### Recommendations

89. It is recommended that;

- a. Each of the factors that presently limit extrapolation of single-wheel laboratory tire performance relations to wheeled vehicle field performance situations be studied in detail, i.e. the influence on tire performance of soil classes (different types of essentially purely cohesive and purely frictional soils, as well as soils possessing both cohesive and frictional strength components), irregular soil strength profiles, and operating characteristics peculiar to a wheeled vehicle (as opposed to a single wheel), and to a somewhat lesser degree (because more is known of their effects), the influence of wheel translational velocity, wheel slip, and tire tread pattern or traction aid.
- b. The effects of all of the factors in a above be evaluated and quantified on the basis of data from carefully controlled laboratory tests; then application of these relations to wheeled vehicle field situations be validated.

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Table 1

## Characteristics of Laboratory Test Tires

Deflection Coefficient $\frac{\delta}{h}$	Load $\frac{W}{h}$	Inflation Pressure psi		Carcass Section Height h, in.		Section Width b, in.		Tire Diameter d, in.	Measured Rolling Circumference ft	Hard-Surface Measurements				
		No Load	Loaded	No Load	Loaded	No Load	Loaded			Contact Area in. <sup>2</sup>	Contact Length in.	Contact Width in.	Contact Pressure psi	
		4.00-7, 2-PR												
0.15	0.0652	100	16.00	16.20	3.09	2.63	4.18	4.40	14.10	3.57	4.89	3.71	1.78	20.45
	0.0664	225	33.00	33.20	3.12	2.64	4.22	4.42	14.16	3.56	6.31	4.20	1.97	35.66
	0.0662	340	51.40	51.80	3.14	2.67	4.26	4.50	14.20	3.59	6.18	4.26	2.00	55.02
	0.0672	455	63.20	63.50	3.18	2.70	4.31	4.50	14.28	3.61	7.29	4.50	2.10	62.41
0.25	0.1083	43	2.05	2.20	3.06	2.30	4.15	4.49	14.04	3.41	11.24	5.10	2.84	3.83
	0.1083	50	2.30	2.43	3.06	2.30	4.15	4.46	14.04	3.41	11.00	5.00	2.80	4.55
	0.1095	63	3.30	3.50	3.07	2.30	4.16	4.48	14.06	3.42	11.81	5.20	2.90	5.33
	0.1094	80	5.20	5.50	3.08	2.31	4.16	4.50	14.08	3.42	10.92	5.05	2.77	7.32
	0.1094	100	6.00	6.20	3.08	2.31	4.17	4.50	14.08	3.43	10.87	5.31	2.65	9.20
	0.1094	114	7.45	7.60	3.08	2.31	4.17	4.50	14.08	3.42	11.62	5.18	2.81	9.81
	0.1094	134	9.70	9.80	3.08	2.31	4.17	4.50	14.08	3.42	10.92	4.97	2.60	12.27
	0.1094	143	10.10	10.20	3.08	2.31	4.17	4.49	14.08	3.42	11.60	5.20	2.77	12.33
	0.1092	155	10.35	10.50	3.09	2.32	4.18	4.50	14.10	3.43	11.62	5.20	2.78	13.34
	0.1092	171	12.80	12.95	3.09	2.32	4.18	4.50	14.10	3.43	12.20	5.21	2.90	14.02
	0.1092	204	14.00	14.20	3.09	2.32	4.18	4.50	14.10	3.43	12.32	5.30	2.89	16.56
	0.1092	225	16.80	17.00	3.09	2.32	4.18	4.50	14.10	3.44	11.53	5.21	2.66	19.51
	0.1105	233	17.30	17.50	3.10	2.32	4.18	4.50	14.12	3.44	11.81	5.24	2.78	19.73
	0.1105	247	18.20	18.40	3.10	2.32	4.18	4.53	14.12	3.44	11.52	5.17	2.76	21.44
	0.1103	340	25.80	26.00	3.11	2.33	4.20	4.57	14.14	3.46	11.58	5.30	2.73	29.36
	0.1103	359	26.60	26.80	3.11	2.33	4.20	4.53	14.14	3.45	12.12	5.30	2.80	29.62
0.35	0.1102	455	34.70	35.00	3.12	2.34	4.22	4.58	14.16	3.47	11.70	5.40	2.72	38.89
	0.1102	480	36.10	36.40	3.12	2.34	4.22	4.58	14.16	3.47	12.11	5.40	2.81	39.64
	0.1102	513	40.00	40.20	3.12	2.34	4.22	4.59	14.16	3.47	12.24	5.37	2.76	41.91
	0.1102	541	45.00	45.00	3.12	2.34	4.22	4.59	14.16	3.49	11.90	5.32	2.76	45.46
	0.1102	570	47.00	47.00	3.12	2.34	4.22	4.60	14.16	3.48	12.11	5.40	2.78	47.07
	0.1524	100	2.50	2.70	3.06	1.99	4.15	4.61	14.04	3.35	15.76	6.20	3.40	6.35
	0.1534	150*	5.50	5.80	3.08	2.00	4.16	4.64	14.08	--	15.67	--	--	9.89
4.00-20, 2-PR	0.1534	225	10.10	10.40	3.09	2.01	4.17	4.68	14.03	3.35	15.55	6.05	3.26	14.46
	0.1532	340	16.70	17.00	3.09	2.01	4.18	4.71	14.10	3.36	15.97	6.16	3.31	21.29
	0.1530	455	21.40	21.90	3.10	2.02	4.20	4.76	14.12	3.36	17.44	6.39	3.43	26.09
	0.08	0.0190	315	82.00	82.00	3.38	3.11	4.36	4.40	28.43	7.35	4.87	4.50	1.40
0.15	0.0336	225	24.50	24.70	3.16	2.69	4.18	4.53	27.99	7.11	9.21	6.00	2.00	24.23
	0.0342	455	48.00	48.20	3.22	2.74	4.22	4.44	28.11	7.16	9.78	6.34	2.00	46.52
	0.0341	670	60.70	61.00	3.23	2.75	4.25	4.50	28.13	7.18	9.92	6.70	2.11	61.35
0.25	0.0559	225	11.80	11.40	3.12	2.34	4.11	4.53	27.91	6.98	16.31	7.36	2.75	13.80
	0.0558	340	18.00	18.20	3.14	2.36	4.15	4.56	27.95	7.00	16.32	7.57	2.75	20.83
	0.0564	455	24.40	24.70	3.16	2.37	4.18	4.56	27.99	7.00	16.47	7.55	2.72	27.63
	0.0570	670	37.20	37.50	3.20	2.40	4.20	4.61	28.07	7.03	16.33	7.75	2.63	41.03
0.35	0.0782	225	6.30	6.70	3.11	2.02	4.05	4.75	27.83	6.87	22.67	8.65	3.34	9.93
	0.0781	340	10.80	11.00	3.12	2.03	4.11	4.82	27.91	6.88	24.60	9.00	3.42	13.82
	0.0788	455	14.70	15.00	3.13	2.03	4.14	4.82	27.93	6.88	24.90	9.06	3.38	18.27
	0.0800	670	22.70	23.00	3.16	2.05	4.17	4.83	27.97	6.89	25.52	9.14	3.42	26.25
	0.0800	720	24.50	24.70	3.16	2.05	4.18	4.82	27.91	6.90	25.26	9.25	3.35	28.50
0.45	0.1009	670	15.40	16.10	3.14	1.73	4.14	5.12	27.95	6.83	33.75	10.55	3.82	19.85
6.00-16, 2-PR														
0.15	0.0559	225	8.30	8.50	5.27	4.48	6.60	6.50	28.26	7.05	20.42	7.20	3.30	11.02
	0.0559	300*	11.20	11.40	5.28	4.49	6.60	6.92	28.28	--	21.54	--	--	13.93
	0.0565	455	17.00	17.20	5.30	4.50	6.61	6.95	28.32	7.04	22.28	7.73	3.34	20.43
	0.0564	670	28.80	29.00	5.32	4.52	6.62	7.00	28.36	7.10	20.52	7.57	3.23	32.65
	0.0564	890	37.70	38.00	5.32	4.53	6.63	7.00	28.38	7.10	21.34	7.65	3.30	41.71
0.25	0.0928	225	4.20	4.50	5.25	3.94	6.60	7.28	28.22	6.90	31.59	8.90	4.30	7.12
	0.0934	455	10.00	10.50	5.27	3.95	6.60	7.22	28.26	6.89	33.95	9.40	4.25	13.40
	0.0933	670	15.00	15.30	5.29	3.97	6.60	7.30	28.30	6.89	35.65	9.61	4.39	18.79
	0.0932	720	15.00	16.20	5.30	3.98	6.60	7.28	28.32	6.89	36.08	9.80	4.38	19.66
	0.0932	890	20.70	21.00	5.30	3.98	6.62	7.28	28.32	6.91	36.09	9.72	4.40	24.66

(Continued)

Note: Many of the values given in British units of measure in this report were obtained by converting metric values given in other reports. Differences in number of significant figures used in this and some of the source reports, rounding of numbers in the conversion process, and the use of values for two or more listed terms to compute another term (in subsequent tables) sometimes caused very slight differences between values of corresponding terms in this and the source reports.

\* Interpolated values.

(1 of 3 sheets)

Table 1 (Continued)

Deflection Coefficient $\frac{W}{b^2}$	Load W lb	Inflation Pressure psi		Carcass Section Height h, in.		Section Width b, in.		Tire Diameter d, in.	Measured Rolling Circumference ft	Hard-Surface Measurements				
		No Load	Loaded	No Load	Loaded	No Load	Loaded			Contact Area in. <sup>2</sup>	Contact Length in.	Contact Width in.	Contact Pressure psi	
6.00-16, 2-PR (Continued)														
0.35	0.1299	225	2.00	2.50	5.23	3.40	6.60	7.72	28.16	6.75	56.35	11.10	6.10	3.99
	0.1302	455	6.50	7.00	5.27	3.43	6.60	7.70	28.26	6.77	50.25	11.20	5.48	9.05
	0.1302	670	10.00	10.30	5.27	3.43	6.60	7.72	28.26	6.78	52.69	11.50	5.27	12.72
	0.1307	890	12.50	13.00	5.29	3.44	6.60	7.72	28.30	6.78	56.76	11.86	5.73	15.68
6.00-16 (Solid)														
0.010	0.0036	225	--	--	5.17	5.12	7.00	7.01	27.84	7.29	1.81	2.12	2.08	120.32
0.025	0.0093	455	--	--	5.17	5.04	7.00	7.01	27.84	7.27	3.05	2.75	1.40	149.18
9.00-14, 2-PR														
0.015	0.0674	225	7.30	7.50	6.31	5.36	8.25	8.50	28.20	6.98	26.60	8.00	4.15	8.46
	0.0678	455	16.20	16.40	6.37	5.41	8.28	8.52	28.32	7.07	26.80	8.20	4.00	16.98
	0.0678	670	25.20	25.40	6.42	5.46	8.30	8.61	28.42	7.16	26.30	8.11	4.00	25.48
	0.0686	890	36.70	37.00	6.50	5.52	8.34	8.61	28.58	7.26	23.90	7.97	3.75	37.24
0.25	0.1113	117	1.30	1.50	6.23	4.67	8.13	8.84	28.04	6.83	51.54	10.50	6.10	2.27
	0.1118	135	1.65	1.90	6.24	4.68	8.15	8.82	28.06	6.83	52.22	10.60	6.12	2.59
	0.1118	155	2.20	2.40	6.24	4.68	8.15	8.81	28.06	6.82	52.31	10.59	6.30	2.96
	0.1112	164	2.40	2.70	6.24	4.68	8.15	8.83	28.06	6.82	52.07	10.50	6.01	3.15
	0.1111	172	2.60	2.80	6.25	4.69	8.17	8.82	28.08	6.83	53.38	10.70	6.20	3.22
	0.1116	191	2.90	3.05	6.28	4.71	8.19	8.80	28.14	6.83	53.10	10.60	6.14	3.60
	0.1116	210	3.00	3.25	6.28	4.71	8.20	8.80	28.14	6.83	53.10	10.74	5.95	3.95
	0.1116	225	3.00	3.25	6.28	4.71	8.20	8.76	28.14	--	53.40	10.96	6.06	4.21
	0.1115	241	3.50	3.70	6.29	4.72	8.24	8.82	28.16	6.84	53.84	10.60	6.10	4.48
	0.1121	279	4.30	4.50	6.30	4.73	8.24	8.82	28.18	6.83	52.72	10.58	6.00	5.29
	0.1121	291	4.45	4.65	6.31	4.73	8.24	8.82	28.18	6.83	50.80	10.43	6.00	5.73
	0.1121	324	4.90	5.10	6.30	4.72	8.24	8.78	28.18	6.82	52.88	10.65	5.90	6.13
	0.1121	340	5.10	5.35	6.30	4.72	8.24	8.79	28.18	6.82	52.58	10.55	6.00	6.47
	0.1121	365	5.50	5.80	6.30	4.72	8.24	8.79	28.18	6.82	52.45	10.60	5.91	6.96
	0.1121	455	7.20	7.50	6.31	4.73	8.25	8.80	28.20	6.78	52.40	10.75	5.80	8.68
	0.1121	488	8.35	8.55	6.31	4.73	8.25	8.81	28.20	6.84	51.26	10.57	5.74	9.52
	0.1121	519	9.00	9.20	6.31	4.73	8.25	8.83	28.20	6.83	51.80	10.52	5.85	10.02
	0.1121	550	9.85	10.20	6.31	4.73	8.25	8.78	28.20	6.83	49.51	10.25	5.70	11.11
	0.1124	610	10.80	11.00	6.36	4.77	8.26	8.82	28.30	6.83	51.32	10.60	5.90	11.89
	0.1124	640	11.20	11.40	6.36	4.77	8.26	8.82	28.30	6.83	51.34	10.60	5.93	12.25
	0.1124	670	11.60	11.80	6.36	4.77	8.26	8.82	28.30	--	50.70	10.64	5.75	13.21
	0.1124	824	15.40	15.60	6.36	4.77	8.26	8.82	28.30	6.82	50.84	10.50	5.80	16.21
	0.1123	870	15.90	16.10	6.37	4.78	8.27	8.87	28.32	6.83	50.34	10.50	5.72	17.28
	0.1123	890	16.20	16.40	6.37	4.78	8.28	8.87	28.32	6.84	50.20	10.63	5.75	17.73
	0.1123	965	18.20	18.40	6.37	4.78	8.26	8.86	28.32	6.93	51.80	10.68	5.80	18.63
	0.1128	1000	18.40	18.70	6.40	4.80	8.30	8.88	28.38	6.87	52.32	10.76	5.85	19.11
	0.1128	1151	22.20	22.30	6.40	4.80	8.30	8.88	28.38	6.92	50.75	10.70	5.66	22.68
	0.1135	1465	29.50	30.20	6.48	4.86	8.31	8.84	28.54	6.98	49.41	10.72	5.60	29.65
	0.1134	1840	38.70	39.00	6.50	4.88	8.34	8.84	28.58	7.03	50.00	10.90	5.53	36.80
0.35	0.1554	225	1.50	2.00	6.24	4.06	8.15	9.22	28.06	6.68	78.70	13.00	7.48	2.86
	0.1561	455	4.00	4.40	6.30	4.10	8.24	9.36	28.18	6.64	82.60	13.18	7.60	5.51
	0.1567	670	7.30	7.50	6.31	4.10	8.25	9.37	28.20	6.57	75.70	12.75	7.14	8.85
	0.1576	890	10.20	10.60	6.36	4.13	8.25	9.36	28.30	6.69	70.10	12.60	7.07	12.70
1.75-26														
0.15	0.0149	100	40.30	42.10	1.40	1.19	1.72	1.84	28.17	6.52	2.20	3.91	0.79	45.45
	0.0149	225	91.00	93.20	1.40	1.19	1.77	1.89	28.17	6.52	2.45	4.14	0.80	91.84
0.35	0.0348	100	12.40	13.30	1.40	0.91	1.69	2.02	28.17	6.44	6.14	6.10	1.27	11.29
	0.0348	225	33.00	34.80	1.40	0.91	1.72	2.01	28.17	6.44	5.92	5.92	1.28	38.01
11.00-20, 12-PR														
0.15	0.0654	3000	--	45.20	9.03	7.68	11.41	11.97	41.31	10.41	59.10	11.44	6.05	55.76
	0.0654	4500	--	63.00	9.03	7.68	11.56	12.11	41.31	10.38	63.45	11.43	6.70	70.92
0.23	0.1094	3000	--	19.00	9.03	6.77	11.31	12.50	41.31	9.98	104.52	15.38	8.04	28.70
0.35	0.1530	3000	--	11.37	9.03	5.87	11.19	13.03	41.31	9.72	136.01	17.86	8.50	22.06
	0.1530	4500	--	21.00	9.03	5.87	11.41	13.03	41.31	9.72	141.45	17.88	8.69	31.61

(Continued)

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Table 1 (Concluded)

Deflection Coefficient b/h	Load W lb	Inflation Pressure psi		Carcass Sec- tion Height h, in.		Section Width b, in.		Tire Diameter d, in.	Measured Rolling Circum- ference ft	Hard-Surface Measurements				
		No Load	Loaded	No Load	Loaded	No Load	Loaded			Contact Area sq in.	Contact Length in.	Contact Width in.	Contact Pressure psi	
16x6.50-8, 2-PR														
0.15	0.0633 0.0651	225 350	18.90 30.70	19.00 30.80	3.43 3.52	2.92 2.99	6.41 6.45	6.48 6.54	16.11 16.29	4.15 4.15	10.82 11.41	3.70 4.00	3.54 3.60	20.79 30.65
0.25	0.1046 0.1068 0.1080 0.1094	225 455 670 890	7.80 18.70 30.60 45.80	8.00 19.00 30.80 46.00	3.31 3.43 3.52 3.60	2.42 2.57 2.64 2.70	6.41 6.41 6.45 6.50	6.65 6.63 6.64 6.77	15.87 16.11 16.29 16.45	3.96 3.99 -- 4.15	21.80 20.22 20.08 20.01	5.50 5.29 5.38 5.45	4.62 4.47 4.48 4.36	10.32 22.50 33.37 44.48
0.35	0.1431 0.1476	225 455	3.75 11.65	4.20 12.00	3.20 3.37	2.08 2.19	6.41 6.41	7.00 6.86	15.65 15.99	3.93 3.95	32.30 30.28	6.95 6.70	5.56 5.37	6.97 15.03
16x11.50-6, 2-PR														
0.15	0.0915 0.0924 0.0942 0.0948	225 455 600 890	8.05 17.70 30.50 45.00	8.10 17.80 31.10 45.00	5.26 5.50 5.65 5.80	4.47 4.68 4.80 4.93	11.12 11.12 11.14 11.15	11.17 11.19 11.20 11.30	17.27 17.75 18.05 18.35	4.47 4.53 4.67 --	25.51 23.36 20.04 20.70	4.71 4.68 4.50 4.55	6.48 6.20 5.82 5.53	8.82 19.48 29.94 43.00
0.25	0.1505 0.1527	225 455	3.25 8.75	3.50 9.00	5.13 5.27	3.85 3.95	11.12 11.12	11.22 11.25	17.01 17.29	4.39 4.43	49.58 46.50	6.80 6.49	8.18 8.09	4.54 9.78
0.35	0.2101 0.2114 0.2154 0.2170	225 455 890 1290	1.30 4.90 12.80 19.00	1.70 4.70 13.20 19.80	5.05 5.14 5.40 5.52	3.28 3.34 3.51 3.59	11.11 11.12 11.12 11.12	11.70 11.68 11.65 11.60	16.85 17.03 17.55 17.79	4.26 4.35 4.42 4.46	82.07 73.90 57.19 58.50	9.30 8.50 7.54 7.88	10.18 9.09 8.23 8.34	2.74 6.16 15.53 21.98
16x15.00-6, 2-PR														
0.08	0.0486	225	15.00	15.00	5.34	4.91	15.20	15.20	17.68	4.50	12.40	1.84	7.42	18.14
0.15	0.0898 0.0897 0.0906	225 273 455	5.60 6.65 13.50	5.60 6.80 14.00	5.19 5.20 5.33	4.41 4.42 4.53	15.20 15.20 15.20	15.20 15.20 15.20	17.38 17.40 17.66	4.32 -- 4.45	22.22 32.32 31.10	2.42 3.50 4.06	9.70 9.75 9.21	10.12 8.45 14.62
0.25	0.1464 0.1496 0.1516	225 455 890	1.80 6.00 15.30	2.50 6.40 15.50	4.97 5.19 5.34	3.73 3.89 4.00	15.20 15.20 15.20	15.21 15.23 15.22	16.94 17.38 17.68	4.21 4.33 4.41	74.49 56.67 47.56	6.36 5.40 5.00	12.55 10.95 10.25	3.02 8.03 18.71
0.35	0.2038 0.2070	225 455	0.65 3.50	1.00 3.90	4.89 5.10	3.18 3.32	15.20 15.20	15.23 15.23	16.78 17.20	4.15 4.24	100.67 67.16	7.70 5.76	14.00 12.20	2.11 6.76
26x16.00-10, 4-PR														
0.15	0.0744 0.0749 0.0751	315 455 890	3.45 6.00 13.90	3.50 6.10 14.00	6.00 6.05 6.15	5.10 5.14 5.23	16.12 16.14 16.15	16.16 16.15 16.18	24.20 24.30 24.50	6.23 6.26 6.31	60.00 67.15 55.33	5.60 6.33 5.70	11.40 11.60 10.95	5.25 6.77 16.09
0.25	0.1240 0.1251	455 1290	2.00 12.00	2.20 12.25	6.00 6.13	4.50 4.60	16.12 16.15	16.32 16.22	24.20 24.46	6.17 6.23	118.27 97.69	9.70 8.20	13.80 13.02	3.85 13.16
0.35	0.1736 0.1736	890 1020	2.20 3.10	2.80 3.90	6.00 6.00	3.90 3.90	16.12 16.12	16.43 16.50	24.20 24.20	6.12 6.17	156.22 157.23	12.30 12.00	15.22 15.08	5.70 6.49
31x15.50-13, 4-PR														
0.08	0.0416	225	7.40	7.50	7.70	7.08	15.00	15.03	29.80	7.56	23.18	4.63	6.00	9.61
0.15	0.0769 0.0776	455 1000	5.45 15.90	5.60 16.10	7.63 7.75	6.49 6.59	15.00 15.02	15.10 15.13	29.66 29.90	7.49 7.58	62.88 56.88	8.25 7.95	9.11 8.75	7.24 17.29
0.25	0.1288 0.1298	890 1200	5.65 9.35	6.00 9.70	7.63 7.75	5.72 5.81	15.00 15.00	15.28 15.29	29.66 29.90	7.36 7.42	105.72 100.35	11.40 11.00	10.97 10.63	8.41 11.95
0.35	0.1797 0.1812	890 1350	3.55 6.85	4.00 7.25	7.60 7.70	4.94 5.00	15.00 15.00	15.57 15.52	29.60 29.80	7.32 7.36	160.39 149.48	14.72 14.21	12.75 12.05	5.55 9.03
Rigid Wheels														
0.00	0.0000	All loads	0.00	0.00	--	--	12.00	12.00	27.90	87.65	Hard-surface contact shape is a line.			
0.00	0.0000	All loads	0.00	0.00	--	--	6.00	6.00	27.80	87.34	Hard-surface contact shape is a line.			
0.00	0.0000	All loads	0.00	0.00	--	--	3.00	3.00	27.90	87.65	Hard-surface contact shape is a line.			

Table 2

Single-Wheel Tests in Yuma Sand, 20 Percent Slip, First Pass (Pneumatic Tires and Rigid Wheels)

Test No.	Penetration Resistance			Design Deflection Coefficient $\frac{W}{h}$	Wheel Load $W$ , lb	Pull, lb $P$	Sinkage $s$ , in.	Torque $M$ , ft.-lb.	Pull Coefficient $\frac{P}{W}$	Sinkage Coefficient $\frac{s}{W}$	Torque Coefficient $\frac{M}{W}$	$\frac{g(bd)^{3/2}}{W} \cdot \frac{A}{h} \cdot \frac{g(bd)^{3/2}}{W} \cdot (1 - \frac{A}{h})^4 \cdot \frac{gbd^2}{V} \cdot (1 - \frac{gbd^2}{V})^{3/2}$		
	$G'$	$G''$	$G$											
4.00-7.5, 2-PR														
164 798A	19.5	20.0	17.3	0.15	0.0652	100	83	18	0.217	0.047	0.382	14.15	151	297
164 824A	20.0	18.3	15.8	0.0652	100	98	113	18	0.265	0.070	0.323	10.94	140	230
164 825A	11.5	11.3	9.8	0.0652	100	100	113	24	0.142	0.089	0.374	5.89	75	184
164 799A	20.0	19.0	16.4	0.0664	225	204	206	38	0.089	0.081	0.327	5.37	71	116
164 800A	15.5	15.0	13.0	0.0664	225	206	9	39	0.044	0.092	0.332	4.37	56	93
164 801A	18.0	17.0	14.7	0.0664	225	204	-3	38	-0.015	0.106	0.327	4.99	64	106
164 821A	12.5	11.3	9.8	0.0664	225	202	5	45	0.025	0.112	0.391	3.36	43	71
164 827A	22.0	20.3	17.6	0.1094	100	117	50	27	0.427	0.065	0.416	16.92	214	314
164 828A	24.0	22.7	19.6	0.1094	100	119	61	31	0.513	0.046	0.470	18.52	234	344
164 831A	30.5	29.0	25.1	0.1092	200	188	60	40	0.319	0.048	0.383	15.10	191	280
164 820A	13.0	12.0	10.4	0.1092	225	231	23	42	0.100	0.080	0.327	5.09	64	94
164 822A	10.0	15.0	13.0	0.1092	225	211	40	39	0.190	0.048	0.333	6.97	88	129
164 829A	24.5	22.7	19.6	0.1092	225	231	53	44	0.229	0.042	0.343	9.60	121	178
164 826A	14.5	14.0	12.1	0.1103	340	339	30	52	0.088	0.105	0.276	4.08	52	76
164 833A	23.0	21.7	18.7	0.1524	100	106	47	28	0.443	0.016	0.489	27.46	440	542
164 834A	21.0	21.0	18.2	0.1534	150	150	55	33	0.367	0.022	0.406	19.04	305	379
165 1A	27.5	26.3	22.8	0.1534	150	143	53	36	0.371	0.045	0.465	25.02	400	498
164 830A	23.5	22.7	19.6	0.1532	225	219	73	48	0.333	0.026	0.405	14.09	226	280
165 2A	5.5	5.0	4.3	0.1532	225	204	-16	38	-0.078	0.215	0.344	3.32	53	66
164 832A	25.0	23.0	19.9	0.1530	455	436	111	87	0.255	0.050	0.367	7.30	117	143
1-66-30	20.0	19.3	16.9	0.1092	225	234	--	51	--	0.092	0.392	8.17	103	151
1-66-31	20.0	19.3	16.7	0.1092	152	154	--	36	--	0.266	0.421	12.27	155	191
1-66-32	22.0	21.0	18.1	0.1094	124	117	--	30	--	0.308	0.462	17.40	220	283
1-66-33	19.6	19.4	17.1	0.1095	63	65	--	18	--	0.374	0.500	29.42	372	466
1-66-34	20.0	19.6	17.4	0.1083	44	42	--	13	--	0.405	0.559	46.06	582	648
1-66-35	18.5	17.8	15.8	0.1103	353	349	--	67	--	0.115	0.345	5.18	65	87
1-66-36	19.5	18.9	16.9	0.1102	450	449	--	91	--	0.087	0.304	4.35	55	81
1-66-37	19.0	19.2	16.2	0.1102	541	534	--	96	--	0.013	0.329	3.50	44	65
4.00-20, 2-PR														
164 790A	6.5	5.3	4.6	0.15	0.0336	225	197	27	0.137	0.092	0.429	4.43	57	101
164 791A	9.5	8.7	7.5	0.0336	225	211	39	89	0.185	0.061	0.368	6.75	86	153
164 793A	20.5	19.0	16.4	0.0336	225	210	54	93	0.257	0.031	0.396	14.82	189	336
164 798A	15.5	14.0	12.1	0.0342	455	416	89	178	0.118	0.079	0.372	5.64	72	128
164 799A	7.5	6.3	5.5	0.0342	455	402	14	177	0.035	0.143	0.382	2.65	34	60
164 792A	12.0	11.0	9.5	0.0342	455	415	32	185	0.077	0.092	0.387	4.44	57	101
164 794A	15.0	14.7	12.7	0.0342	455	425	57	180	0.134	0.059	0.368	5.79	74	132
164 795A	19.0	18.7	16.1	0.0342	455	420	66	170	0.157	0.054	0.352	7.43	95	169
165 14A	28.0	27.7	24.4	0.0559	225	216	76	107	0.352	0.016	0.438	39.39	447	690
165 15A	17.5	16.7	14.4	0.0559	225	233	80	111	0.343	0.022	0.421	18.98	240	313

Continued

(Continued)

\*  $G'$ ,  $G''$ , and  $G$  are each defined in Appendix A. Measurement  $G$  is the only term used to describe penetration resistance gradient in the body of this report. Only one nominal soil strength value is listed in reference 7 for all the tests with rigid wheels.

\*\*  $P'$  is actual pull plus  $ma$  (mass times acceleration) measured in a programmed-increasing-slip test. See Appendix A for a more detailed explanation.

(1 of 6 sheets)

Table 2

Single-Wheel Tests in Yuma Sand, 20 Percent Slip, First Pass (Pneumatic Tires and Rigid Wheels)

Test No.	Penetration Resistance			Design Deflection Coefficient $\frac{\delta}{h}$	Wheel Load W, lb	Full, lb $P_{max}$	Sinkage S, in.	Torque M, ft-lb	Pull Coefficient $\frac{P}{W}$	Sinkage Coefficient $\frac{s}{d}$	Torsion Coefficient $\frac{M}{Wr}$	$\frac{\alpha(\delta d)^{3/2}}{W} \cdot \left(1 - \frac{\delta}{h}\right)^{-1/4}$	$\frac{\alpha d^2}{W} \cdot \left(1 - \frac{\delta}{h}\right)^{-1/8} \cdot \frac{\alpha^{3/2}}{s}$
	G'	G	G''										
164 798A	19.5	20.0	17.3	0.15	100	83	0.66	18	0.217	--	0.382	14.15	297
164 824A	20.0	18.3	15.8	0.0652	100	98	0.26	18	0.265	--	0.323	10.94	230
164 825A	11.5	11.3	9.8	0.0652	100	113	1.26	24	0.142	--	0.374	5.89	124
164 799A	20.0	19.0	16.4	0.0664	225	204	1.15	38	0.044	--	0.327	5.57	118
164 800A	15.5	15.0	13.0	0.0664	225	206	1.30	39	0.044	--	0.332	4.57	93
164 801A	18.0	17.0	14.7	0.0664	225	204	1.50	38	-0.015	--	0.327	4.99	106
164 821A	12.5	11.3	9.8	0.0664	225	202	1.59	45	0.025	--	0.351	3.36	71
164 827A	22.0	20.3	17.6	0.1094	100	117	0.91	27	0.427	--	0.416	16.92	314
164 828A	24.0	22.7	19.6	0.1094	100	119	0.65	31	0.513	--	0.470	18.52	344
164 831A	30.5	29.0	25.1	0.1092	200	188	0.60	40	0.319	--	0.343	15.10	280
164 820A	13.0	12.0	10.4	0.1092	225	231	1.13	42	0.100	--	0.327	5.09	94
164 822A	16.0	15.0	13.0	0.1092	225	211	0.67	39	0.290	--	0.333	6.97	129
164 829A	24.5	22.7	19.6	0.1092	225	231	0.59	44	0.229	--	0.343	9.60	178
164 826A	14.5	14.0	12.1	0.1103	340	339	1.48	52	0.088	--	0.276	4.08	76
164 833A	23.0	21.7	18.7	0.1524	100	106	0.22	28	0.443	--	0.489	27.46	942
164 834A	21.0	21.0	18.2	0.1524	150	150	0.31	33	0.367	--	0.406	19.04	379
165 1A	27.5	26.3	22.8	0.1534	150	143	0.64	36	0.371	--	0.465	25.02	498
164 830A	23.5	22.7	19.6	0.1532	225	219	0.57	48	0.333	--	0.405	14.09	280
165 2A	5.5	5.0	4.3	0.1532	225	204	3.03	38	-0.078	--	0.215	3.32	66
164 832A	25.0	23.0	19.9	0.1530	455	436	0.71	87	0.255	--	0.367	7.30	143
1-66-30	20.0	19.3	16.9	0.1092	225	234	0.73	51	--	0.192	0.392	8.17	103
1-66-31	20.0	19.3	16.7	0.1092	152	154	0.41	36	--	0.266	0.421	12.27	157
1-66-32	22.0	21.0	18.1	0.1094	124	117	0.54	30	--	0.308	0.462	17.40	220
1-66-33	19.6	19.4	17.1	0.1095	63	65	0.25	18	--	0.374	0.500	29.42	323
1-66-34	20.0	19.6	17.4	0.1083	44	42	0.20	13	--	0.405	0.559	46.06	346
1-66-35	18.5	17.8	15.8	0.1103	353	349	0.91	67	--	0.115	0.345	5.18	97
1-66-36	19.5	18.9	16.9	0.1102	450	449	1.17	91	--	0.087	0.364	4.35	81
1-66-37	19.0	19.2	16.2	0.1102	541	534	1.59	98	--	-0.013	0.359	3.50	65
164 790A	6.5	5.3	4.6	0.0336	225	197	2.57	97	0.137	--	0.429	4.43	1

\*  $G'_0$ ,  $G'$ , and  $G$  are each defined in Appendix A. Measurement  $G$  is the only term used to describe penetration resistance gradient in relations described in the body of this report. Only one nominal soil strength value is listed in reference 7 for all the tests with rigid wheels.

\*\*\*  $p'$  is actual pull plus  $m a$  (mass times acceleration) measured in a programmed-increasing-slip test. See Appendix A for a more detailed explanation.

(1 of 6 sheets)

Table 2 (Continued)

[illegible]

Table 2 (Continued)

Test No.	Penetration			Design Deflection Coefficients M/A	Wheel Load P, lb	Pull P, lb	Sluggage M, lb	Torque T, lb-in	Pull Coefficient P/P <sub>0</sub>	Sluggage Coefficient M/M <sub>0</sub>	Stress		$\frac{d(\Delta y)}{dy} \cdot \frac{1}{\Delta y} \cdot \frac{1}{\Delta y} \cdot \frac{1}{\Delta y}$	$\frac{d(\Delta y)}{dy} \cdot \frac{1}{\Delta y} \cdot \frac{1}{\Delta y} \cdot \frac{1}{\Delta y}$	$\frac{d(\Delta y)}{dy} \cdot \frac{1}{\Delta y} \cdot \frac{1}{\Delta y} \cdot \frac{1}{\Delta y}$	$\frac{d(\Delta y)}{dy} \cdot \frac{1}{\Delta y} \cdot \frac{1}{\Delta y} \cdot \frac{1}{\Delta y}$
	q, psi	d, in	q, psi								q, psi	d, in				
169 9A	11.4	1.3	10.7	0.25	0.112	190	141	90	0.932	0.001	65.61	0.378	0.378	199	199	199
169 9A	12.4	1.3	11.2	0.112	0.112	235	219	111	0.493	0.016	44.81	0.540	0.540	896	896	896
169 7A	26.0	26.0	22.4	0.112	0.112	285	216	130	0.465	0.012	21.22	0.844	0.844	174	174	174
169 6A	14.4	14.4	13.4	0.112	0.112	455	438	241	0.458	0.007	23.16	0.703	0.703	448	448	448
169 5A	13.4	13.4	12.4	0.112	0.112	670	619	280	0.458	0.006	23.06	0.607	0.607	291	291	291
169 4A	3.4	3.4	3.4	0.112	0.112	670	619	280	0.458	0.006	23.06	0.607	0.607	64	64	64
169 3A	2.4	2.4	2.4	0.112	0.112	670	619	280	0.458	0.006	23.06	0.607	0.607	48	48	48
169 2A	2.4	2.4	2.4	0.112	0.112	670	619	280	0.458	0.006	23.06	0.607	0.607	63	63	63
169 1A	15.4	15.4	15.4	0.112	0.112	990	840	293	0.458	0.006	23.06	0.607	0.607	61	61	61
169 3A	17.4	17.4	17.4	0.112	0.112	990	840	293	0.458	0.006	23.06	0.607	0.607	189	189	189
169 9A	22.5	22.5	20.7	0.15	0.154	287	243	139	0.958	0.003	103.11	0.607	0.607	211	211	211
169 11A	15.0	15.0	14.0	0.154	0.154	287	243	139	0.958	0.003	103.11	0.607	0.607	1419	1419	1419
169 12A	27.5	27.5	24.2	0.156	0.156	670	446	362	0.465	0.009	45.13	0.502	0.502	782	782	782
169 13A	4.0	4.0	3.7	0.156	0.156	670	634	314	0.160	0.096	7.83	0.396	0.396	110	110	110
169 10A	1.3	1.3	1.3	0.156	0.156	800	863	430	0.377	0.051	17.84	0.456	0.456	286	286	286
169 50	21.5	21.5	19.3	0.25	0.115	935	841	134	0.461	0.002	72.60	0.577	0.577	918	918	918
169 51	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 52	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 53	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 54	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 55	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 56	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 57	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 58	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 59	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 60	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 61	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 62	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 63	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 64	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 65	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 66	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 67	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 68	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 69	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 70	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 71	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 72	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 73	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 74	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 75	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 76	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 77	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 78	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 79	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 80	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 81	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 82	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 83	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 84	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 85	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 86	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 87	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 88	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 89	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 90	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 91	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 92	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 93	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 94	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 95	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 96	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 97	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 98	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 99	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 100	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 101	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 102	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 103	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 104	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 105	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 106	19.4	19.4	17.6	0.112	0.112	350	347	166	0.441	0.000	44.87	0.551	0.551	567	567	567
169 107	19.4	19.4	1													

Table 2 (Continued)

Test No.	Penetration Resistance, psi/in.		Design Deflection Coefficient $\frac{\Delta}{\delta}$	Wheel Load $\frac{W}{lb}$	Full Load $\frac{P}{lb}$	Singeage $\frac{S}{in.}$	Torque $\frac{M}{in.-lb}$		Singeage Coef. $\frac{S}{A}$	Torque Coef. $\frac{M}{N \cdot r}$	$\frac{Q(bd)^{3/2}}{V}$		$\frac{Q(bd)^{3/2}}{V} \cdot (1 - \frac{h}{b})^4$		$\frac{Q(bd)^2}{V} \cdot (1 - \frac{h}{b})^3$		$\frac{Q(bd)}{V} \cdot (1 - \frac{h}{b})^2$	
	$\frac{Q_1}{lb}$	$\frac{Q_2}{lb}$		Design Load $\frac{W}{lb}$	Full Load $\frac{P}{lb}$		11.75-26 (Continued)	11.75-26, 12-72			$\frac{Q(bd)^{3/2}}{V}$	$\frac{Q(bd)^{3/2}}{V}$	$\frac{Q(bd)^{3/2}}{V} \cdot (1 - \frac{h}{b})^4$	$\frac{Q(bd)^{3/2}}{V} \cdot (1 - \frac{h}{b})^4$	$\frac{Q(bd)^2}{V} \cdot (1 - \frac{h}{b})^3$	$\frac{Q(bd)^2}{V} \cdot (1 - \frac{h}{b})^3$	$\frac{Q(bd)}{V} \cdot (1 - \frac{h}{b})^2$	$\frac{Q(bd)}{V} \cdot (1 - \frac{h}{b})^2$
1-1 13A	24	24.7	13.6	100	91	0.71	12	12	0.021	0.308	10.90	10.90	139	139	331	331	...	...
1-1 13A	16	12.3	10.7	285	226	2.47	86	86	0.068	0.397	2.90	2.90	32	32	75	75	...	...
1-1 13A	11	7.0	6.1	225	200	4.44	77	77	0.130	0.359	1.61	1.61	23	23	48	48	...	...
1-1 13A	10	4.3	7.2	225	225	4.33	90	90	0.154	0.359	1.77	1.77	21	21	53	53	...	...
1-1 11A	27	22.3	14.3	225	287	1.98	84	84	0.076	0.319	4.51	4.51	58	58	135	135	...	...
1-1 10A	25	14.0	12.1	100	104	0.97	39	39	0.034	0.325	13.38	13.38	214	214	207	207	...	...
1-1 10A	14	4.3	4.5	100	61	2.35	34	34	0.083	0.324	6.95	6.95	111	111	106	106	...	...
1-1 10A	10	7.3	6.1	100	69	2.04	35	35	0.072	0.307	7.32	7.32	127	127	113	113	...	...
1-1 10A	17	12.3	10.7	225	226	2.87	79	79	0.081	0.303	5.29	5.29	69	69	86	86	...	...
1-1 11A	17	5.7	4.9	225	206	4.66	77	77	0.165	0.324	2.81	2.81	45	45	43	43	...	...
1-1 10A	14	7.7	6.7	225	203	4.33	48	48	0.162	0.205	3.84	3.84	79	79	76	76	...	...
1-1 10A	14	11.3	9.9	225	234	2.88	46	46	0.081	0.170	4.94	4.94	79	79	59	59	...	...
1-1 10A	10	7.3	6.1	225	230	3.69	86	86	0.138	0.324	3.23	3.23	52	52	50	50	...	...
2-1 25A	17.5	21.0	19.2	3000	3000	...	...	...	0.076	0.076	9.31	9.31	119	119	203	203	...	...
2-1 25A	17.5	10.0	16.4	3000	3000	...	...	...	0.082	0.082	8.39	8.39	107	107	183	183	...	...
2-1 25A	12.5	14.7	12.7	3000	3000	...	...	...	0.103	0.103	6.50	6.50	83	83	142	142	...	...
2-1 25A	10.2	10.4	10.4	3000	3000	...	...	...	0.111	0.111	5.32	5.32	68	68	116	116	...	...
2-1 25A	7.3	6.3	6.3	3000	3000	...	...	...	0.124	0.124	3.22	3.22	43	43	70	70	...	...
2-1 25A	10.4	7.3	10.9	3000	3000	...	...	...	0.097	0.097	10.18	10.18	130	130	222	222	...	...
2-1 25A	11.7	11.7	11.7	3000	3000	...	...	...	0.081	0.081	6.04	6.04	77	77	132	132	...	...
2-1 25A	11.7	11.7	11.7	3000	3000	...	...	...	0.131	0.131	3.22	3.22	41	41	70	70	...	...
2-1 25A	7.3	6.3	6.3	3000	3000	...	...	...	0.086	0.086	6.92	6.92	88	88	150	150	...	...
2-1 25A	23.0	19.2	19.2	4500	4500	...	...	...	0.007	0.007	5.64	5.64	72	72	122	122	...	...
2-1 25A	19.7	14.1	14.1	4500	4500	...	...	...	0.123	0.123	4.90	4.90	63	63	106	106	...	...
2-1 25A	11.2	11.2	11.2	4500	4500	...	...	...	0.086	0.086	2.61	2.61	50	50	84	84	...	...
2-1 25A	3.7	7.3	7.3	4500	4500	...	...	...	0.076	0.076	13.86	13.86	171	171	269	269	...	...
2-1 25A	17.3	15.0	15.0	3000	3000	...	...	...	0.087	0.087	11.61	11.61	144	144	226	226	...	...
2-1 25A	15.3	13.2	13.2	3000	3000	...	...	...	0.076	0.076	10.22	10.22	126	126	199	199	...	...
2-1 25A	11.3	11.3	11.3	3000	3000	...	...	...	0.081	0.081	8.67	8.67	107	107	168	168	...	...
2-1 25A	11.3	6.3	6.3	3000	3000	...	...	...	0.088	0.088	7.29	7.29	94	94	147	147	...	...
2-1 25A	7.3	6.3	6.3	3000	3000	...	...	...	0.060	0.060	10.76	10.76	60	60	99	99	...	...
2-1 25A	20.7	17.0	17.0	3000	3000	...	...	...	0.050	0.050	13.77	13.77	332	332	430	430	...	...
2-1 25A	17.2	14.7	14.7	3000	3000	...	...	...	0.044	0.044	11.77	11.77	301	301	389	389	...	...
2-1 25A	14.1	11.7	11.7	3000	3000	...	...	...	0.055	0.055	10.77	10.77	252	252	327	327	...	...
2-1 25A	11.5	12.7	11.0	3000	3000	...	...	...	0.050	0.050	12.75	12.75	204	204	264	264	...	...
2-1 25A	7.0	4.3	7.2	3000	3000	...	...	...	0.093	0.093	8.35	8.35	134	134	173	173	...	...
2-1 25A	14.3	22.3	12.3	4500	4500	...	...	...	0.054	0.054	15.16	15.16	246	246	315	315	...	...
2-1 25A	14.3	14.3	14.3	4500	4500	...	...	...	0.057	0.057	12.33	12.33	201	201	258	258	...	...
2-1 25A	14.3	14.3	14.3	4500	4500	...	...	...	0.087	0.087	10.23	10.23	166	166	212	212	...	...
2-1 25A	12.2	13.0	12.0	4500	4500	...	...	...	0.103	0.103	8.28	8.28	132	132	170	170	...	...
2-1 25A	11.6	12.0	12.0	4500	4500	...	...	...	0.115	0.115	5.73	5.73	92	92	118	118	...	...
2-1 25A	7.3	7.2	7.2	4500	4500	...	...	...	0.133	0.133	...	...	...	...	...	...	...	...

\* The 11.00-20, 12.75 tires were used by deadweight, so that test load very nearly equaled design load.

\*\* Values of  $\frac{Q(bd)^{3/2}}{V}$  reported herein are slightly different from those reported in reference 2 of literature cited; this results since (a) somewhat more precise measurements of  $b$  and  $d$  are used herein than in reference 2, and (b) values of  $Q$  instead of  $Q_1$  are used herein.

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Table 2 (Concluded)

Test No.	Penetration		Design Deflection Coefficient $\frac{2\Delta}{h}$	Wheel Load W, lb	Full, lb	Sinkage $\frac{h}{2}$ , in.	Torque N, ft-lb	Pull Coefficient $\frac{P}{W}$	Sinkage Coef- ficient $\frac{f}{d}$	Torque Coef- ficient $\frac{M}{Wf}$	$\frac{A}{W}$ $\frac{G(bd)^{3/2}}{W}$	$\frac{G(bd)^{3/2}}{W}$ $\frac{1}{(1-\frac{1}{b})}$	$\frac{G(bd)^{3/2}}{W}$ $\frac{1}{(1-\frac{1}{b})}$ $\frac{1}{(1-\frac{1}{b})}$	$\frac{G(bd)^{3/2}}{W}$ $\frac{1}{(1-\frac{1}{b})}$ $\frac{1}{(1-\frac{1}{b})}$	$\frac{G(bd)^{3/2}}{W}$ $\frac{1}{(1-\frac{1}{b})}$ $\frac{1}{(1-\frac{1}{b})}$	$\frac{G(bd)^{3/2}}{W}$ $\frac{1}{(1-\frac{1}{b})}$ $\frac{1}{(1-\frac{1}{b})}$	$\frac{G(bd)^{3/2}}{W}$ $\frac{1}{(1-\frac{1}{b})}$ $\frac{1}{(1-\frac{1}{b})}$	$\frac{G(bd)^{3/2}}{W}$ $\frac{1}{(1-\frac{1}{b})}$ $\frac{1}{(1-\frac{1}{b})}$	$\frac{G(bd)^{3/2}}{W}$ $\frac{1}{(1-\frac{1}{b})}$ $\frac{1}{(1-\frac{1}{b})}$
	$\frac{Q}{P}$	$\frac{Q}{P}$																	
Wheel diam = 27.00 in.; wheel width = 12 in.; active radius = 1.1625 ft																			
1-A	--	10.0	9.3	--	--	94	55	0.32	50	0.372	--	0.011	0.498	--	--	--	--	923	--
2-A	--	--	--	--	--	170	55	0.40	89	0.324	--	0.014	0.451	--	--	--	--	911	--
3-A	--	--	--	--	--	268	73	0.40	130	0.272	--	0.014	0.417	--	--	--	--	925	--
4-A	--	--	--	--	--	375	86	1.23	178	0.229	--	0.044	0.409	--	--	--	--	232	--
5-A	--	--	--	--	--	572	86	0.82	275	0.150	--	0.029	0.414	--	--	--	--	152	--
6-A	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
7-A	--	--	--	--	--	100	42	0.20	55	0.420	--	0.007	0.473	--	--	--	--	869	--
8-A	--	--	--	--	--	208	63	0.42	108	0.303	--	0.015	0.416	--	--	--	--	418	--
9-A	--	--	--	--	--	295	71	0.46	143	0.241	--	0.016	0.417	--	--	--	--	294	--
Wheel diam = 27.00 in.; wheel width = 6 in.; active radius = 1.1625 ft																			
10-A	--	10.8	9.3	--	--	108	30	0.47	60	0.278	--	0.017	0.480	--	--	--	--	399	--
11-A	--	--	--	--	--	182	40	0.74	86	0.220	--	0.027	0.408	--	--	--	--	237	--
12-A	--	--	--	--	--	292	49	0.92	129	0.168	--	0.033	0.392	--	--	--	--	109	--
13-A	--	--	--	--	--	385	44	1.25	175	0.114	--	0.045	0.393	--	--	--	--	148	--
14-A	--	--	--	--	--	585	17	1.56	270	0.029	--	0.071	0.399	--	--	--	--	112	--
15-A	--	--	--	--	--	188	38	0.72	92	0.202	--	0.026	0.422	--	--	--	--	73	--
Wheel diam = 27.00 in.; wheel width = 3 in.; active radius = 1.1625 ft																			
16-A	--	10.8	9.3	--	--	93	25	0.45	42	0.269	--	0.016	0.389	--	--	--	--	233	--
17-A	--	--	--	--	--	188	32	1.13	87	0.170	--	0.041	0.398	--	--	--	--	115	--
18-A	--	--	--	--	--	285	36	1.71	135	0.126	--	0.061	0.408	--	--	--	--	76	--
19-A	--	--	--	--	--	370	33	2.26	176	0.089	--	0.081	0.409	--	--	--	--	56	--
20-A	--	--	--	--	--	380	30	2.20	190	0.079	--	0.079	0.430	--	--	--	--	19	--

Rigid Wheel

Tests conducted at 25% slip.

For the rigid wheels, active radius = one-half the wheel diameter, expressed in feet.

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Table 3

## Single-Wheel Tests in Yuma Sand, Toward Point, First Pass (Pneumatic Tires)

Test No.	Penetration Resistance Gradient, $\psi$ psi/in.			Design Deflection Coefficient		Wheel Load $W$ , lb		Towed Force, $\psi$ lb		Sinkage $z$ , in.	Slip $s$ , %	Towed Force Coefficient		Sinkage Coefficient $\psi/d$	$G(hd)^{3/2}$	$\frac{z}{h}$
	$G_0$	$G'$	$G$	$b/h$	$2b/d$	Design	Test	$P_T$	$P_T$			$P_T/h$	$P_T/h$			
4.00-7, 2-PR																
164 798A	19.5	20.0	17.3	0.15	0.0692	100	85	22	--	0.38	-7.5	0.259	--	0.027	13.81	
164 824A	20.0	18.3	15.8		0.0692	100	106	12	--	0.70	-3.1	0.113	--	0.050	10.12	
164 825A	11.5	11.3	9.8		0.0692	100	123	21	--	0.99	-7.0	0.171	--	0.070	5.41	
164 800A	15.5	15.0	13.0		0.0694	225	210	64	--	0.74	-12.4	0.305	--	0.052	4.29	
164 827A	22.0	20.3	17.6	0.25	0.1071	100	121	3	--	2.64	-2.5	0.025	--	0.045	16.36	
165 828A	24.0	22.7	19.6		0.1094	100	122	4	--	0.52	-1.2	0.033	--	0.037	18.07	
164 831A	30.5	29.0	25.1		0.1092	200	185	24	--	0.38	-5.7	0.130	--	0.027	15.35	
164 822A	15.0	15.0	13.0		0.1092	225	215	30	--	0.35	-4.2	0.137	--	0.025	6.81	
164 829A	24.5	22.7	19.6		0.1092	225	234	25	--	0.20	-2.9	0.107	--	0.014	9.47	
164 825A	14.5	14.0	12.1		0.1103	340	348	73	--	1.17	-7.0	0.210	--	0.083	3.98	
164 832A	23.0	21.7	18.7	0.35	0.1524	100	109	13	--	0.00	-4.4	0.119	--	0.000	26.71	
164 834A	21.0	21.0	18.2		0.1534	150	152	13	--	0.04	-3.8	0.085	--	0.003	18.79	
165 1A	27.5	26.3	22.8		0.1534	150	145	15	--	0.30	-3.9	0.103	--	0.021	24.57	
164 830A	23.5	22.7	19.6		0.1532	224	224	17	--	0.60	-3.8	0.075	--	0.004	13.78	
164 832A	25.0	23.0	19.9		0.1530	455	440	55	--	0.37	-3.0	0.125	--	0.025	7.23	
4.00-20, 2-PR																
164 791A	9.5	8.7	7.5	0.15	0.0335	225	218	46	--	1.30	-11.3	0.211	--	0.046	6.52	
164 793A	20.5	19.0	16.4		0.0335	225	221	26	--	0.59	-1.9	0.118	--	0.021	14.09	
164 782A	15.5	14.0	12.1		0.0342	455	426	105	--	1.77	-10.9	0.246	--	0.053	5.50	
164 794A	15.0	14.7	12.7		0.0342	455	440	100	--	1.18	-9.2	0.227	--	0.042	5.59	
164 795A	19.0	18.7	16.1		0.0342	455	446	87	--	1.34	-7.6	0.195	--	0.043	7.00	
165 14A	28.0	32.0	27.7	0.25	0.0559	225	227	18	--	0.00	-2.6	0.079	--	0.000	37.48	
165 15A	17.5	16.7	14.4		0.0559	225	238	11	--	0.29	-2.0	0.045	--	0.010	18.58	
165 19A	18.5	18.7	16.1		0.0558	340	338	21	--	0.25	-1.9	0.062	--	0.009	14.68	
165 16A	15.0	15.0	13.0		0.0564	455	450	70	--	0.76	-2.0	0.156	--	0.027	9.14	
165 21A	29.5	29.7	25.6	0.35	0.0782	225	233	15	--	0.39	-2.7	0.064	--	0.014	16.16	
165 22A	29.5	29.7	25.6		0.0781	340	350	10	--	0.24	-1.8	0.029	--	0.009	31.45	
165 20A	19.5	19.0	16.4		0.0788	455	442	21	--	0.26	-0.9	0.048	--	0.009	15.15	
6.00-16, 2-PR																
164 802A	6.3	6.7	5.8	0.15	0.0559	225	213	33	--	1.03	-8.8	0.155	--	0.036	10.40	
164 805A	14.0	14.0	12.1		0.0559	225	215	15	--	0.00	-2.8	0.070	--	0.020	21.50	
164 809A	17.7	18.0	15.6		0.0559	225	222	13	--	0.20	-2.6	0.059	--	0.027	24.85	
164 808A	14.3	14.3	12.4		0.0559	300	293	19	--	0.20	-2.5	0.065	--	0.027	16.19	
164 807A	11.4	12.0	10.4		0.0565	455	458	60	--	0.94	-3.3	0.131	--	0.033	8.72	
165 35A	4.6	4.7	4.0		0.0564	670	650	292	--	3.50	-37.6	0.549	--	0.124	2.37	
164 816A	15.1	15.7	13.5	0.25	0.0928	225	240	10	--	0.28	-1.3	0.042	--	0.010	35.74	
165 37A	17.1	17.3	15.0		0.0928	225	223	14	--	0.04	-1.3	0.063	--	0.001	42.74	
164 818A	18.3	18.0	15.6		0.0934	455	455	18	--	0.30	-3.3	0.040	--	0.011	21.83	
165 33A	2.6	2.7	2.3		0.0934	455	429	182	--	3.58	-39.3	0.424	--	0.127	3.41	
164 812A	15.7	16.0	13.8		0.0932	890	865	76	--	0.71	-9.2	0.068	--	0.025	10.24	
164 317A	10.6	11.0	9.5		0.0932	890	863	173	--	1.53	-8.1	0.200	--	0.054	7.06	
164 803A	6.3	6.7	5.8	0.35	0.1299	225	225	26	--	0.51	-4.5	0.116	--	0.018	22.88	
164 813A	19.4	19.0	16.4		0.1299	225	239	11	--	0.16	-1.1	0.046	--	0.006	60.92	
164 814A	19.4	20.0	17.3		0.1302	455	446	8	--	0.04	-1.3	0.018	--	0.001	34.58	
165 34A	3.7	4.0	3.5		0.1302	670	674	246	--	3.60	-30.9	0.365	--	0.127	4.63	
164 811A	16.0	17.3	15.0		0.1307	890	870	48	--	0.34	-2.3	0.055	--	0.012	15.40	
9.00-14, 2-PR																
164 774A	9.0	9.3	8.1	0.15	0.0674	225	230	12	--	0.24	-2.7	0.052	--	0.009	18.75	
164 773A	6.5	7.3	6.3		0.0674	225	225	21	--	0.58	-4.7	0.093	--	0.021	14.90	
164 760A	15.0	16.0	13.8		0.0674	225	230	17	--	0.42	-4.2	0.074	--	0.015	31.94	
164 766A	19.5	20.7	17.9		0.0674	225	232	6	--	0.42	-2.2	0.066	--	0.015	41.07	
164 777A	9.5	10.3	8.9		0.0678	455	460	52	--	1.01	-4.7	0.113	--	0.036	10.42	
164 782A	13.0	14.3	12.4		0.0678	455	458	71	--	0.72	-2.5	0.065	--	0.025	14.48	
164 783A	5.5	6.0	5.2		0.0678	455	435	94	--	1.81	-11.9	0.216	--	0.064	6.42	
164 785A	20.0	20.3	17.6		0.0678	455	460	21	--	0.16	-2.4	0.046	--	0.016	20.41	
164 781A	12.8	14.0	12.1		0.0685	890	871	154	--	1.61	-4.2	0.177	--	0.056	7.67	
164 784A	19.2	19.7	17.0		0.0686	890	864	74	--	0.88	-0.9	0.066	--	0.031	12.86	
165 5A	11.8	12.3	10.7	0.25	0.1112	150	144	7	--	0.00	-0.5	0.049	--	0.000	64.24	
165 1A	12.8	13.9	11.2		0.1116	225	225	7	--	0.18	-2.0	0.031	--	0.006	43.62	
165 7A	24.5	25.0	22.5		0.1116	225	216	6	--	0.18	-0.8	0.028	--	0.006	91.28	
165 6A	14.5	14.3	12.4		0.1121	455	447	28	--	0.43	-2.4	0.063	--	0.015	24.67	
165 27A	13.8	13.7	11.8		0.1121	455	455	15	--	0.40	-3.4	0.032	--	0.014	22.51	
165 28A	7.7	8.0	7.5		0.1124	670	646	253	--	3.05	-29.7	0.356	--	0.108	4.77	
165 3A	15.5	16.0	13.8		0.1127	890	870	30	--	0.02	-1.7	0.035	--	0.001	14.57	
165 24A	17.8	17.3	15.0		0.1123	890	862	35	--	0.18	-2.9	0.041	--	0.006	15.62	
165 9A	22.5	24.0	20.7	0.35	0.1554	225	243	18	--	0.00	0.4	0.074	--	0.000	103.11	
165 11A	15.0	15.0	13.0		0.1554	225	225	13	--	0.02	0.2	0.058	--	0.001	69.63	
165 12A	27.5	28.0	24.2		0.1567	670	668	22	--	0.00	-0.5	0.031	--	0.000	44.99	
165 13A	4.0	4.3	3.7		0.1567	670	653	129	--	2.04	-13.8	0.198	--	0.072	7.04	
165 10A	13.8	14.3	12.4		0.1576	890	892	39	--	0.00	-0.9	0.044	--	0.000	17.36	

(Continued)

\*  $G_0$ ,  $G'$ , and  $G$  are as defined in Appendix A. Measurement  $G$  is the only term used to describe penetration resistance gradient in relations described in the body of this report.

\*\*  $P_T$  is towed force,  $\psi$  as  $\psi$  (mass times acceleration) measured in a programmed-increasing-slip test. See Appendix A for a more detailed explanation.

† Sinkage  $z$  at the towed point.

Table 3 (Continued)

Test No.	Penetration Resistance Gradient, psi/in.			Design Deflection Coefficient		Wheel Load W, lb		Towed Force, lb		Sinkage z, in.	Slip S %	Towed Force Coefficient		Sinkage Coefficient z/d	G(bd) <sup>3/2</sup> W	
	C <sub>b</sub>	C'	G	b/h	2b/d	Design	Test	P <sub>T</sub>	P <sub>T</sub>			P <sub>T</sub> /W	P <sub>T</sub> /W		W	h
9.00-14, 2-PR (Continued)																
1-65-64	14.5	15.1	13.3	0.25	--	152	155	--	2	0.00	1.2	--	0.013	0.000	73.71	
1-65-65	13.0	13.4	11.8	--	--	141	144	--	5	0.00	1.0	--	0.035	0.000	70.85	
1-65-66	14.0	14.1	12.7	--	--	239	243	--	5	0.00	1.5	--	0.021	0.000	46.18	
1-65-67	13.5	14.2	11.6	--	--	237	237	--	6	0.00	1.4	--	0.025	0.000	43.25	
1-65-68	14.2	14.7	13.2	--	--	613	650	--	19	0.02	2.0	--	0.029	0.008	18.14	
1-65-69	11.8	12.2	10.3	--	--	839	821	--	57	0.00	-7.2	--	0.065	0.000	11.21	
1-65-70	14.2	14.6	13.2	--	--	360	318	--	6	0.00	0.8	--	0.017	0.000	33.55	
1-65-71	11.5	12.0	9.7	--	--	291	286	--	7	0.00	1.0	--	0.024	0.000	30.00	
1-65-72	12.0	12.7	10.3	--	--	160	163	--	0	0.00	2.0	--	0.000	0.000	54.63	
1-65-74	12.2	13.0	11.0	--	--	455	458	--	13	0.00	6.6	--	0.028	0.000	21.31	
1.75-26 Bicycle																
161 504A	10	8.0	6.9	0.15	0.0149	100	102	25	--	1.89	-9.9	0.245	--	0.067	3.42	
161 510A	24	22.7	19.6	--	--	100	114	13	--	0.64	-1.0	0.114	--	0.023	8.70	
161 499A	20	14.3	12.4	--	--	100	110	27	--	1.15	-7.5	0.193	--	0.041	4.18	
161 503A	13	7.0	6.1	--	--	225	212	78	--	3.52	-15.8	0.368	--	0.125	1.52	
161 508A	10	8.3	7.2	--	--	225	216	95	--	3.99	-18.6	0.440	--	0.141	1.76	
161 511A	27	22.3	19.3	--	--	225	256	61	--	1.47	-8.1	0.238	--	0.052	3.98	
161 497A	16	12.3	10.6	--	--	225	258	79	--	2.24	-12.4	0.306	--	0.080	2.17	
161 505A	10	7.3	6.3	0.35	0.0248	100	91	18	--	1.63	-6.4	0.198	--	0.058	7.96	
161 502A	8	6.3	5.4	--	--	100	93	21	--	1.85	-8.1	0.226	--	0.066	6.68	
161 500A	20	14.0	12.1	--	--	100	133	7	--	0.63	-0.5	0.053	--	0.022	10.46	
161 509A	10	7.3	6.3	--	--	225	201	75	--	3.46	-17.4	0.373	--	0.123	3.70	
161 498A	17	12.3	10.6	--	--	225	253	82	--	2.12	-11.5	0.324	--	0.075	4.95	
161 507A	14	11.3	9.8	--	--	225	261	73	--	2.10	-10.3	0.280	--	0.075	4.43	
16x6.50-8, 2-PR																
A68-0066-1	--	--	13.7	0.15	0.0633	225	234	23	26	--	--	0.098	0.111	--	9.22	
A68-0069-1tt	--	--	1.2	0.15	0.0633	225	214	--	14	--	--	--	0.533	--	3.09	
A68-0072-1tt	--	--	10.0	0.15	0.0651	350	346	--	83	--	--	--	0.240	--	4.67	
A68-0057-1	--	--	16.1	0.25	0.1046	225	224	6	7	--	--	0.027	0.031	--	18.44	
A68-0073-1tt	--	--	10.7	0.25	0.1080	670	665	--	308	--	--	--	0.463	--	4.33	
A68-0052-1	--	--	6.2	0.35	0.1431	225	230	30	30	--	--	0.130	0.130	--	9.48	
A68-0068-1	--	--	20.2	0.35	0.1476	455	452	18	18	--	--	0.040	0.040	--	16.23	
A68-0071-1tt	--	--	4.6	0.35	0.1476	455	430	--	308	--	--	--	0.716	--	3.89	
16x11.50-6, 2-PR																
A68-0077-1	--	--	6.2	0.15	0.0915	225	216	24	27	--	--	0.111	0.125	--	11.46	
A68-0084-1tt	--	--	4.8	0.15	0.0924	455	453	--	190	--	--	--	0.419	--	4.41	
A68-0067-1tt	--	--	6.9	0.15	0.0948	890	863	--	492	--	--	--	0.570	--	3.51	
A68-0081-1	--	--	10.1	0.25	0.1505	225	225	7	11	--	--	0.031	0.049	--	29.06	
A68-0078-1	--	--	6.7	0.25	0.1527	455	456	49	67	--	--	0.107	0.147	--	9.79	
A68-0085-1tt	--	--	4.8	0.25	0.1527	455	460	--	105	--	--	--	0.228	--	6.95	
A68-0083-1	--	--	13.1	0.35	0.2101	225	234	8	16	--	--	0.034	0.068	--	50.19	
A68-0082-1	--	--	13.9	0.35	0.2154	670	581	73	73	--	--	0.083	0.083	--	13.04	
16x15.00-6, 2-PR																
A68-0097-1	--	--	15.9	0.15	0.0898	225	230	1	4	--	--	0.004	0.017	--	44.52	
A68-0092-1	--	--	6.9	0.15	0.0897	273	279	26	29	--	--	0.093	0.104	--	15.96	
A68-0096-1	--	--	11.6	0.25	0.1165	225	229	4	7	--	--	0.017	0.031	--	52.32	
A68-0095-1	--	--	8.7	0.25	0.1446	455	448	32	32	--	--	0.071	0.071	--	20.85	
A68-0094-1	--	--	11.2	0.35	0.2070	455	459	9	19	--	--	0.020	0.041	--	36.10	
A68-0089-1	--	--	5.0	0.35	0.2070	455	467	47	55	--	--	0.101	0.118	--	15.84	
26x16.00-10, 4-PR																
A68-0101-1	--	--	6.4	0.15	0.0749	455	459	34	36	--	--	0.074	0.078	--	16.25	
A68-0100-1	--	--	5.0	0.15	0.0751	890	865	174	176	--	--	0.201	0.203	--	6.82	
A68-0102-1	--	--	11.9	0.25	0.1240	455	467	13	13	--	--	0.028	0.028	--	49.08	
A68-0105-1	--	--	5.9	0.25	0.1251	1286	1283	162	162	--	--	0.126	0.126	--	9.03	
A68-0103-1	--	--	12.1	0.35	0.1735	890	896	98	98	--	--	0.109	0.109	--	36.42	
A68-0104-1	--	--	4.5	0.35	0.1735	1020	1036	161	161	--	--	0.155	0.155	--	10.41	
31x15.50-13, 4-PR																
A68-0111-1	--	--	17.5	0.15	0.0767	455	451	4	4	--	--	0.009	0.009	--	54.62	
A68-0107-1	--	--	9.8	0.25	0.1291	1200	1205	71	71	--	--	0.059	0.059	--	19.11	
A68-0110-1	--	--	12.1	0.35	0.1604	890	887	39	39	--	--	0.044	0.044	--	48.36	

Table 4

Single-Wheel Tests in Yuma Sand, 20 Percent Slip, First-Pass, Design Translational Velocities from 0.8 to 18 ft/sec

Test No.	Penetration Resistance Gradient			Wheel Load W, lb	Sinkage s, in.	Torque M, ft-lb	Pull P, lb	Pull Coefficient P/W	Sinkage Coefficient s/d	$\frac{Q(b)}{W} \frac{3}{2} \cdot \frac{b}{h}$	$\frac{V}{V_{th}}$	Wheel Translational Velocity		Soil Confining Pressure <sup>a</sup> Beneath Tire CP, psi		Shear Wave Velocity $V_{sh}$ , ft/sec	$\frac{Q(b)}{W} \frac{3}{2} \cdot \frac{b}{h} \cdot \left( \frac{150V}{V_{sh}} \right)^{1/2}$	$\frac{150V}{V_{sh}} \cdot \frac{1}{h}$
	$\frac{dp}{ds}$ , lb/in.											ft/sec		ft/sec				
	$Q_b$	$Q'$	$Q$									$V$	$V_{th}$	Newmark Chart	From Tire Contact Pressure			
1	12.5	20.3	1.1	216	0.53	129	92	0.426	0.019	74.82	1.25	1.49	1.19	1.22	396	0.731	53.93	
2	12.5	19.3	1.1	236	0.15	137	94	0.407	0.006	61.03		1.24	1.30	1.32	405	0.677	47.32	
3	12.5	19.0	1.2	433	0.49	183	124	0.378	0.017	43.03		1.24	1.28	1.31	450	0.643	27.07	
4	12.5	18.0	1.2	454	0.47	237	153	0.350	0.017	31.66		1.21	2.60	2.62	491	0.608	19.85	
5	12.5	17.0	1.2	481	0.41	204	172	0.300	0.019	4.14		1.20	8.51	8.44	681	0.514	8.13	
6	12.2	13.0	1.2	871	0.93	365	215	0.250	0.033	17.39		1.18	5.11	5.07	591	0.547	9.91	
7	12.2	13.5	1.4	851	0.94	369	214	0.254	0.034	18.32		1.18	5.00	4.94	587	0.550	10.08	
8	12.5	13.0	1.4	830	1.28	382	202	0.242	0.045	18.65		1.21	4.90	4.88	585	0.557	10.39	
9	21.5	22.0	1.6	241	0.30	154	111	0.461	0.000	72.60	5	5.19	1.33	1.37	410	1.378	100.04	
10	13.8	20.3	1.6	347	0.00	212	153	0.441	0.000	44.87		4.96	1.96	1.99	455	1.279	57.39	
11	12.2	15.0	1.6	279	0.30	166	113	0.442	0.000	44.72		4.91	1.49	1.51	421	1.322	59.18	
12	13.0	14.1	1.6	194	0.00	121	89	0.459	0.000	70.34		4.92	1.04	1.09	384	1.386	57.49	
13	12.2	13.0	1.6	134	0.32	97	61	0.455	0.011	70.97		4.92	0.68	0.74	345	1.463	103.83	
14	12.8	12.7	1.6	126	0.00	83	59	0.468	0.000	75.48		4.97	0.64	0.68	337	1.487	118.24	
15	12.5	12.1	1.6	80	0.00	112	80	0.455	0.000	55.28		4.90	0.95	0.97	372	1.406	77.72	
16	12.5	12.2	1.6	148	0.00	109	77	0.458	0.000	56.13		4.98	0.88	0.94	369	1.423	79.83	
17	11.0	11.2	1.8	199	0.53	127	90	0.452	0.019	43.07		5.01	1.07	1.12	387	1.394	60.04	
18	11.5	14.1	1.2	230	0.20	137	95	0.413	0.007	46.49		4.90	1.27	1.28	402	1.352	68.85	
19	14.3	12.1	1.2	342	0.10	196	139	0.406	0.004	32.85		4.97	1.92	1.97	451	1.286	42.25	
20	13.2	11.9	1.2	340	0.41	196	141	0.415	0.015	30.96		4.93	1.92	1.96	451	1.281	39.66	
21	12.5	12.8	1.6	443	0.15	286	183	0.337	0.020	17.97		4.94	3.14	3.15	517	1.197	21.51	
22	11.0	13.1	1.1	537	0.12	300	187	0.313	0.022	17.36		4.95	3.48	3.46	530	1.184	20.55	
23	14.5	13.1	1.3	150	0.08	92	68	0.453	0.003	76.66		5.09	0.78	0.81	354	1.469	118.61	
24	11.0	13.4	1.6	144	0.47	95	52	0.431	0.017	70.85		5.09	0.73	0.79	351	1.475	104.90	
25	14.5	12.7	1.2	240	0.12	148	105	0.438	0.004	46.76		5.15	1.30	1.37	410	1.373	64.20	
26	13.5	14.2	1.1	240	0.12	149	110	0.458	0.004	42.72		5.07	1.32	1.37	410	1.362	56.17	
27	14.2	14.7	1.2	634	0.75	337	209	0.320	0.027	18.03		4.99	3.80	3.76	547	1.170	21.10	
28	11.5	12.2	1.0	800	1.08	404	254	0.246	0.038	11.50		4.93	4.68	4.65	577	1.132	13.02	
29	14.5	14.7	1.2	344	0.16	197	137	0.398	0.006	33.94		5.04	1.92	1.97	457	1.286	43.65	
30	11.5	13.0	1.2	286	0.41	166	115	0.402	0.015	30.00		5.01	1.60	1.62	429	1.329	39.87	
31	12.5	12.1	1.3	156	0.00	106	77	0.464	0.000	53.65		5.01	0.88	0.94	368	1.436	77.04	
32	12.0	13.3	1.1	449	0.45	252	148	0.374	0.016	21.73		5.04	2.59	2.59	489	1.243	27.01	
33	12.2	13.5	1.1	444	0.32	244	148	0.377	0.011	21.88		5.06	2.56	2.57	489	1.246	27.01	
34	11.0	13.1	1.4	114	0.14	79	56	0.475	0.009	68.55	13	12.70	0.60	0.65	332	2.395	164.18	
35	12.5	13.1	1.1	178	0.14	114	79	0.500	0.005	58.15		12.70	0.89	0.94	369	2.256	131.19	
36	11.0	11.5	1.0	152	0.00	125	81	0.474	0.000	46.01		12.70	1.02	1.09	388	2.216	101.96	

(Continued)

<sup>a</sup> Test values of  $V_{sh}$  were used in computations involving this variable.<sup>b</sup> Soil confining pressure beneath the tire at depth  $w$  was estimated (a) by use of a rectangular approximation of tire contact shape, measured properties of Yuma sand, a Newmark chart, and the procedures in reference 10, and (b) by dividing measured hard-surface tire contact pressure (table 1) by 3.4. Values of  $V_{th}$  were obtained from fig. 6 using values of  $Q$  estimated by method (b).

Table 4 (Continued)

Test No.	Penetration Resistance Gradient			Wheel Test Load W, lb	Sinkage z, in.	Torque M, ft-lb	Pull Coefficient P/M	Sinkage Coefficient z/d	$\frac{d(ba)^{3/2}}{W} \cdot \frac{\delta}{h}$	Wheel Translational Velocity $V_w$ , ft/sec	Soil Confining Pressure Beneath Tire CP, psi		Shear Wave Velocity $V_{sh}$ , ft/sec	$\left(\frac{150V}{V_{sh}}\right)^{1/2}$	$\frac{d(ba)^{3/2}}{W} \cdot \frac{1}{h} \cdot \left(\frac{150V}{V_{sh}}\right)^{1/2}$	
	$\frac{Q_1}{Q_2}$	$\frac{Q_1}{Q_2}$	$\frac{Q_1}{Q_2}$								From Tire Contact Chart	From Tire Contact Chart				
9.00-14, 2-PR Tire; Design Deflection Coefficient $\frac{\delta}{h} = 0.25$ (Continued)																
1-65-78	12.8	13.5	11.2	322	0.02	216	0.475	0.001	30.17	13	12.70	1.61	1.84	445	2.069	63.66
79	10.8	11.3	9.9	472	1.34	280	0.390	0.048	18.61	13	12.35	2.72	2.74	497	1.931	39.94
80	11.5	12.0	10.0	130	0.00	85	0.446	0.000	66.26	13	13.01	0.68	0.75	346	2.375	157.37
81	10.8	11.4	9.4	498	0.08	256	0.380	0.003	18.21	13	12.65	2.62	2.65	493	1.962	55.73
82	14.0	15.2	12.2	157	0.00	102	0.452	0.000	67.18	13	12.75	0.81	0.88	362	2.298	15.38
83	3.8	4.1	3.1	612	3.35	311	0.072	0.118	4.53	13	12.15	3.52	3.47	535	1.846	5.36
1-65-47	10.0	10.0	8.4	957	1.68	377	0.146	0.059	7.83	5	4.89	5.63	5.59	607	1.099	8.66
48	9.5	9.8	8.1	1155	2.56	508	0.094	0.090	5.34	5	4.80	6.83	6.79	641	1.060	6.72
49	6.2	6.3	5.3	1098	3.70	502	0.036	0.121	3.86	13	5.16	6.50	6.43	632	1.107	4.83
50	2.5	2.8	2.1	180	4.52	245	0.002	0.160	3.77	13	13.03	2.71	2.76	498	1.981	7.69
51	3.0	3.3	2.7	269	2.32	138	0.190	0.082	8.88	13	12.92	1.50	1.53	426	2.133	18.94
4.00-7, 2-PR Tire; Design Deflection Coefficient $\frac{\delta}{h} = 0.25$																
1-65-18	19.5	19.0	17.0	218	1.30	38	0.055	0.092	8.82	0.8	0.85	7.60	5.62	608	0.458	4.04
19	18.5	18.5	16.7	217	0.92	34	0.055	0.066	8.71	0.8	0.84	5.51	5.53	605	0.456	3.97
20	19.5	19.2	16.9	221	0.84	40	0.104	0.060	8.65	1.25	1.22	5.68	5.68	614	0.522	4.77
21	20.5	19.8	17.5	158	0.54	30	0.190	0.038	12.53	1.25	1.26	4.14	4.12	558	0.568	7.12
22	20.5	19.9	17.5	124	0.71	28	0.242	0.050	15.87	1.25	1.26	3.33	3.31	524	0.601	9.54
23	19.5	19.3	17.2	69	0.35	17	0.319	0.025	27.88	1.25	1.25	1.93	1.91	432	0.659	18.37
24	20.4	19.2	17.5	46	0.45	20	0.348	0.032	42.30	3.5	1.30	1.22	1.37	410	0.690	29.19
25	20.4	19.5	17.1	223	0.57	45	0.166	0.040	8.74	3.5	3.56	5.71	7.25	653	0.904	7.50
26	15.5	18.7	16.7	148	0.72	36	0.250	0.051	12.69	3.5	3.64	3.90	3.90	549	0.997	12.65
27	20.4	19.6	16.8	125	0.67	29	0.288	0.048	15.11	3.5	3.45	3.34	3.31	524	0.994	15.03
28	20.4	19.8	17.0	65	0.25	17	0.369	0.018	29.2	3.5	3.52	1.85	1.84	445	1.089	31.85
29	19.0	18.3	16.1	54	0.33	16	0.370	0.024	33.15	3.5	3.48	1.58	1.54	427	1.105	36.63
30	20.0	19.3	16.9	234	0.73	51	0.192	0.052	8.17	5	4.93	6.02	6.03	620	1.092	8.92
31	20.0	19.3	16.7	154	0.40	31	0.266	0.028	12.27	5	5.00	4.02	4.04	554	1.104	14.28
32	22.0	21.0	18.1	117	0.54	31	0.308	0.038	17.40	5	5.15	3.14	3.12	516	1.224	21.30
33	19.6	19.4	17.1	65	0.25	18	0.354	0.018	29.42	5	5.13	1.85	1.82	444	1.316	38.72
34	20.0	19.1	17.4	42	0.20	13	0.405	0.014	46.06	5	5.10	1.38	1.32	405	1.374	63.29
35	18.5	17.8	15.8	349	0.91	67	0.115	0.064	5.18	5	5.16	8.90	8.82	690	1.059	5.19
36	19.5	18.9	16.9	449	1.17	91	0.087	0.083	4.35	5	5.35	11.40	11.26	734	1.045	4.55
37	19.0	19.2	16.2	534	1.55	98	0.013	0.112	3.50	5	4.98	13.44	13.31	734	0.982	3.44
38	22.5	21.6	18.8	494	1.57	92	0.000	0.118	4.38	3.5	3.48	12.50	12.35	753	0.832	3.64
39	21.0	19.8	17.2	63	2.15	77	0.098	0.152	1.25	1.25	1.24	11.74	11.62	742	0.499	2.14
40	22.0	20.8	17.2	22	0.47	53	0.264	0.033	8.59	13	13.07	6.02	6.03	620	1.778	25.27
41	20.0	20.8	17.7	169	0.29	45	0.331	0.021	11.85	13	13.38	4.18	4.34	566	1.803	21.69
42	22.0	20.0	16.3	121	0.18	34	0.380	0.013	15.15	13	13.22	3.25	3.24	582	1.806	27.97
43	20.0	18.9	16.3	557	1.04	106	0.118	0.073	3.38	13	12.84	14.08	13.94	784	1.567	5.30
44	9.5	8.4	6.7	350	2.45	85	0.040	0.173	2.19	18	12.73	8.92	8.82	690	1.663	3.64
45	19.0	18.0	15.0	54	0.04	17	0.463	0.003	31.13	18	13.04	1.58	1.54	427	2.140	70.90
46	18.5	18.4	16.4	44	0.00	13	0.477	0.000	41.44	18	13.14	1.33	1.32	405	2.206	91.42
47	15.3	13.3	10.6	180	0.59	50	0.317	0.042	6.66	18	17.71	4.67	4.65	577	2.149	14.31
48	14.5	13.6	11.0	104	0.35	33	0.394	0.025	12.55	18	17.71	2.83	2.79	500	2.305	28.93
49	14.5	13.4	11.0	56	0.10	19	0.500	0.007	21.84	18	17.17	1.62	1.62	429	2.450	53.51

Table 5  
Single-Wheel Tests in Mortar Sand, 20 Percent Slip, First Pass (Pneumatic Tires)

Test No.	Mortar Sand Penetration Gradient		Design Reflection Coefficient $\frac{h}{h}$	Wheel Load		Pull, lb $P$	Sinkage $z$ , in.	Torque $M$ ft.-lb.	Pull Coefficient		Sinkage Coefficient $\frac{z}{d}$	Torque Coefficient $\frac{M}{W \cdot r}$	Relative Density $D_r$	Yuma Sand Penetration Resistance Gradient, * $G_y$ psi/in.		$G_y$ (bd) $3/2$ $\frac{W}{h}$
	$G_M$	$G_H$		W, lb Design Test	$P$				$\frac{P}{W}$	$\frac{P}{W}$						
	9.00-14, 2-PR Tire†															
523	11.0	9.2	0.15	890	14	--	2.66	314	0.016	--	0.098	0.313	0.69	6.5		4.2
551	8.7	7.4		890	36	--	3.67	322	-0.041	--	0.135	0.320	0.82	5.1		3.2
557	17.3	15.1		890	130	--	1.32	314	0.148	--	0.049	0.311	0.85	11.0		6.9
549	4.7	4.1		890	42	--	4.60	324	-0.048	--	0.170	0.321	0.43	7.8		1.8
556	13.7	12.2		890	83	--	1.75	320	0.094	--	0.065	0.316	0.78	8.7		5.5
554	11.0	9.9	0.35	890	212	--	1.42	332	0.249	--	0.052	0.359	0.72	7.0		9.2
544	3.7	2.9		890	854	--	3.21	299	-0.026	--	0.118	0.322	0.82	4.2		2.2
558	18.6	15.8		890	883	--	0.44	468	0.345	--	0.016	0.425	0.87	11.5		16.3
550	7.7	5.9		890	886	--	2.93	293	0.050	--	0.108	0.304	0.55	4.1		5.8
555	12.7	11.1		890	889	--	1.10	360	0.289	--	0.041	0.394	0.75	7.9		11.1
16x6.50-8, 2-PR Tire††																
A-69-0022-2	14.8	12.8	0.15	225	214	40	0.47	36	0.187	0.126	0.029	0.260	0.80	9.2		6.7
23	17.3	14.9	0.25	225	212	69	0.08	52	0.326	0.254	0.005	0.390	0.85	10.8		13.0
24	25.8	22.4	0.35	455	445	137	0.00	107	0.308	0.263	0.000	0.390	0.98	16.6		13.3
16x11.50-6, 2-PR Tire†																
A-69-0019-2	8.3	7.7	0.15	225	212	49	0.43	45	0.231	0.160	0.025	0.310	0.63	5.4		10.1
33	14.0	12.1	0.15	225	207	79	0.24	59	0.382	0.280	0.014	0.416	0.78	8.7		16.6
20	9.1	7.5	0.25	455	438	92	0.75	108	0.210	0.174	0.043	0.371	0.62	5.2		7.9
21	16.8	14.6	0.35	890	868	256	0.47	250	0.288	0.258	0.027	0.431	0.84	10.6		11.4
16x15.00-6, 2-PR Tire††																
A-69-0033-2	10.6	9.0	0.15	225	217	63	0.31	57	0.290	0.240	0.018	0.387	0.68	6.3		18.2
31	9.0	7.8	0.25	890	870	76	1.38	187	0.087	0.062	0.078	0.316	0.64	5.5		6.9
1	3.6	3.3	0.35	455	448	97	1.38	121	0.217	0.176	0.081	0.425	0.36	2.2		7.2
26x16.00-10, 4-PR Tire††																
A-69-0025-2	6.5	5.2	0.15	890	879	81	2.17	302	0.092	0.066	0.089	0.350	0.51	3.6		4.8
26	9.3	7.3	0.25	1285	1236	242	1.18	427	0.196	0.165	0.048	0.362	0.62	5.1		8.1
27	13.5	11.8	0.35	890	896	366	0.00	420	0.408	0.362	0.000	0.509	0.77	8.4		25.3
31x15.50-13, 4-PR Tire††																
A-69-0028-2	19.6	17.0	0.15	455	451	211	0.00	264	0.468	0.415	0.000	0.493	0.89	12.4		38.8
30	11.6	9.7	0.25	1280	1171	355	321	576	0.303	0.274	0.026	0.422	0.71	6.9		14.0
29	3.8	3.2	0.35	1350	1308	292	2.17	598	0.223	0.186	0.073	0.405	0.35	2.1		5.3

\* Penetration resistance gradient  $G_y$  measured in mortar sand was converted to the corresponding measurement in Yuma sand  $G_y$  by the method described in paragraph 32.

†† P' is actual pull (P) plus  $m$  (mass times acceleration) from a programmed-increasing-slip test. See Appendix A for a more detailed explanation.

† Data taken from table 7 of reference 15.

†† Data taken from table 7 of reference 7.

Table 6  
Single-Wheel Tests in Fat Clay, 20 Percent Slip (Ten Pneumatic Tires and One Solid-Rubber Tire)

Passes Completed	Average Penetration Resistance C, psi	Design Deflection Coefficient D/R	Wheel Load		Average Pull, lb P	Sinkage** z, in.	Average Torque N ft.-lb.	Full Coefficient P/A	Sinkage Coefficient z/d	Torque Coefficient M/Nr <sub>g</sub>	$\frac{C d^2}{W} \cdot \left(1 - \frac{b}{h}\right)^2 \cdot \frac{1}{1 + \frac{b}{2d}}$	$C b^{1/2} \frac{3}{d^{1/2}} \cdot \left(1 + \frac{b}{d}\right)^{1/2}$	$\frac{C A}{W}$
			Design	Avg									
5	56	0.15	100	112	79	0.25	13	0.705	0.018	0.676	11.41	88.40	2.44
5	45	0.0582	100	109	57	0.30	40	0.823	0.021	0.646	9.42	72.99	2.02
3	26	0.0582	100	94	28	0.00	20	0.298	0.043	0.374	6.31	36.95	1.35
4	16	0.0665	225	230	69	0.16	54	0.300	0.032	0.412	4.63	36.05	1.26
3	66	0.0665	225	230	105	0.33	69	0.457	0.023	0.266	5.78	51.72	0.81
5	41	0.0582	340	336	52	1.10	66	0.155	0.077	0.343	2.86	22.16	1.75
5	22	0.0582	340	331	129	0.62	89	0.378	0.044	0.456	3.94	35.15	1.20
5	66	0.0672	455	438	42	1.17	78	0.096	0.082	0.310	2.29	17.79	1.09
3	36	0.0672	455	441	116	1.02	98	0.263	0.071	0.386	3.57	27.77	1.09
5	16	0.1094	100	117	121	0.10	65	1.034	0.007	1.002	10.55	93.58	4.27
5	63	0.1094	100	103	35	0.00	55	0.806	0.000	0.953	15.64	115.54	6.65
5	26	0.1094	100	102	35	0.04	22	0.343	0.003	0.309	7.48	60.67	2.77
5	44	0.1092	225	220	99	0.21	66	0.150	0.017	0.540	2.30	67.23	2.22
5	62	0.1092	225	229	113	0.42	68	0.193	0.030	0.532	5.65	45.84	2.22
5	37	0.1103	340	330	72	0.70	69	0.218	0.070	0.376	3.78	30.79	1.47
5	66	0.1103	340	341	138	0.40	91	0.405	0.028	0.475	5.75	46.82	2.28
5	37	0.1102	455	440	19	1.40	72	0.043	0.099	0.294	2.51	20.41	1.70
1	65	0.1102	455	448	148	0.79	111	0.330	0.056	0.444	3.77	35.22	1.70
5	34	0.1532	225	218	90	0.31	60	0.443	0.022	0.508	5.42	49.07	2.43
5	66	0.1532	225	224	200	0.00	103	0.891	0.000	0.890	10.23	92.71	4.58
2	35	0.1532	340	328	57	0.94	66	0.174	0.067	0.371	3.83	34.61	1.75
5	66	0.1532	340	337	204	0.22	118	0.605	0.016	0.615	6.83	61.75	3.13
2	38	0.1544	455	440	22	0.93	70	0.050	0.066	0.293	2.64	27.55	1.51
5	68	0.1544	455	449	215	0.50	138	0.479	0.035	0.566	5.31	49.32	2.64
5	26	0.25	50	51	--	45	26	--	0.882	0.921	14.85	119.66	5.61
5	43	0.1102	180	181	--	50	90	--	0.103	0.334	8.21	21.57	1.08
5	33	0.1091	204	205	--	71	57	--	0.346	0.501	14.69	38.41	1.93
5	38	0.1094	143	153	--	62	45	--	0.405	0.530	6.35	28.12	2.83
5	22	0.1092	178	185	--	26	42	--	0.141	0.409	3.50	28.37	1.41
5	21	0.1091	199	195	--	29	45	--	0.149	0.416	3.17	23.69	1.33
5	18	0.08	315	308	123	0.71	170	0.395	0.025	0.470	5.46	57.26	0.75
5	22	0.08	0.0190	301	78	1.54	143	0.259	0.054	0.405	2.56	26.86	0.35
5	20	0.15	0.0316	225	196	1.13	91	0.296	0.040	0.405	4.62	40.07	0.94
5	32	0.0316	225	221	135	0.32	153	0.611	0.011	0.604	9.84	85.28	2.02
5	38	0.0316	225	214	89	0.55	107	0.416	0.020	0.436	6.30	32.73	1.33
5	27	0.0312	455	381	22	2.26	160	0.058	0.084	0.365	2.02	18.84	1.05
5	16	0.0312	455	448	181	0.56	226	0.101	0.023	0.438	4.72	40.95	1.05
5	32	0.0342	455	447	130	1.69	194	0.297	0.046	0.386	3.36	29.20	0.72
5	43	0.0341	670	628	191	1.10	276	0.304	0.039	0.381	3.54	30.61	0.83

(continued)

\* P<sup>1</sup> is actual pull plus m<sub>a</sub> (mass times acceleration) measured in a programmed-increasing-slip test. See Appendix A for a more detailed explanation.  
\* First-pass data.

(2 of 5 sheets).

Table 6 (Continued)

Test No.	Phases Com- pleted	Average Penetration Resistance C, psi	Design Deflection Coefficient D/H	Wheel Load K, lb Design	Avg Tent	Average Pull, lb P	Sinkage S, in.	Average Torque M, ft-lb	Pull Coefficient P/H	Sinkage Coefficient S/D	Torque Coefficient M/H <sup>2</sup>	$\frac{CD \cdot \left(\frac{S}{H}\right)^{1/2}}{W}$	$\frac{CD \cdot \left(\frac{S}{H}\right)^{1/2}}{W} \cdot \left(1 - \frac{S}{H}\right)^{-2}$	$\frac{CD \cdot \left(\frac{S}{H}\right)^{1/2}}{W} \cdot \left(1 - \frac{S}{H}\right)^{-2} \cdot \left(\frac{1 + \frac{S}{H}}{1 + \frac{S}{H}}\right)^{1/2}$
270C	5	22	0.25	225	201	92	0.61	108	0.158	0.022	0.175	5.85	20.79	19.99
276C	5	32	0.0559	225	228	104	0.10	196	0.1851	0.004	0.760	12.18	43.32	101.16
280C	5	33	0.0559	225	213	106	0.33	109	0.149	0.012	0.453	8.89	4.43	70.76
272C	5	19	0.0564	455	370	41	2.23	156	0.111	0.080	0.372	2.80	9.94	23.85
274C	5	18	0.0564	455	446	206	0.47	238	0.162	0.017	0.171	5.86	20.83	19.98
288C	5	33	0.0564	455	438	134	1.31	201	0.306	0.047	0.405	4.10	14.58	34.99
281C	5	47	0.0570	670	640	176	1.00	260	0.275	0.036	0.358	4.03	14.32	34.17
291C	5	10	0.0570	670	652	180	1.59	290	0.376	0.057	0.391	3.36	11.96	11.00
293C	5	54	0.0570	670	638	192	0.66	263	0.301	0.024	0.363	1.64	16.50	39.73
277C	5	50	0.0782	225	210	247	0.00	253	1.176	0.000	1.100	14.83	59.35	126.18
283C	5	29	0.0782	225	233	139	0.35	147	0.597	0.011	0.565	7.75	21.02	5.40
286C	5	19	0.0782	225	222	92	0.85	113	0.414	0.030	0.556	5.33	21.33	65.96
278C	5	30	0.0788	455	434	295	0.43	327	0.680	0.015	0.674	7.88	29.35	45.36
284C	5	30	0.0788	455	442	139	0.54	190	0.314	0.034	0.385	4.32	17.20	62.12
295C	5	19	0.0788	455	406	89	1.81	179	0.219	0.065	0.394	2.98	11.92	36.60
285C	5	15	0.0800	670	635	187	0.78	218	0.234	0.028	0.349	4.55	18.22	25.23
282C	5	35	0.0800	670	649	173	1.23	270	0.267	0.028	0.372	3.17	13.87	36.62
289C	5	32	0.0800	670	632	249	1.41	291	0.391	0.015	0.372	5.20	21.15	20.39
285C	5	32	0.0800	720	688	230	0.75	283	0.335	0.027	0.364	4.68	19.53	44.55
400C	5	43	0.45	670	657	263	0.80	334	0.460	0.029	0.460	5.28	26.02	45.82
403C	4	22	0.45	670	621	5	2.85	212	0.008	0.105	0.309	2.56	12.62	22.22
321C	5	20	0.15	225	221	88	0.69	117	0.398	0.024	0.463	5.85	20.92	53.37
329C	5	40	0.0559	225	235	168	0.16	193	0.715	0.006	0.718	11.01	39.35	109.38
325C	5	20	0.0555	455	423	80	1.87	165	0.189	0.066	0.340	3.07	10.97	28.11
331C	5	55	0.0555	455	451	234	0.24	277	0.519	0.008	0.536	7.92	28.29	72.51
327C	5	20	0.0564	670	614	6	2.72	224	0.010	0.096	0.318	2.12	7.58	19.41
319C	5	10	0.0564	670	660	216	1.15	324	0.327	0.041	0.427	3.95	14.10	36.11
334C	5	21	0.0564	890	818	-3	3.04	320	-0.004	0.107	0.340	1.68	5.99	15.32
344C	5	37	0.0564	890	863	175	1.49	332	0.203	0.053	0.335	2.80	10.00	25.59
359C	5	54	0.0564	890	868	276	1.06	420	0.318	0.037	0.421	4.06	14.51	37.13
322C	5	20	0.0928	225	238	104	0.43	134	0.437	0.015	0.502	7.01	24.91	63.96
320C	5	12	0.0928	225	232	247	0.34	280	1.065	0.012	1.076	15.07	53.67	137.80
326C	5	19	0.0934	455	430	84	1.47	173	0.195	0.032	0.588	3.69	13.12	31.84
337C	5	51	0.0934	455	456	357	0.30	241	0.783	0.011	0.783	9.34	33.21	85.64
328C	5	20	0.0933	670	606	35	2.42	210	0.058	0.085	0.308	2.76	9.61	25.30
340C	5	26	0.0933	670	663	241	0.72	341	0.363	0.025	0.458	16.15	16.15	43.63
341C	5	50	0.0933	670	652	352	0.45	439	0.547	0.016	0.547	6.37	23.67	58.44
338C	5	22	0.0932	720	676	66	1.93	240	0.083	0.068	0.316	2.72	9.69	23.67
324C	1	50	0.0932	720	707	283	0.67	267	0.400	0.024	0.461	5.92	21.03	54.66
333C	3	21	0.0932	890	840	-32	3.30	274	-0.038	0.117	0.590	2.10	7.46	19.21
337C	3	21	0.0932	890	826	-18	3.12	275	-0.022	0.110	0.596	2.13	7.59	19.53
345C	3	37	0.0932	890	878	210	1.27	349	0.239	0.045	0.353	3.54	12.58	32.38
360C	5	52	0.0932	890	879	305	0.63	421	0.347	0.022	0.426	4.97	17.65	45.45

(Continued)

(2 of 5 sheets)

Table 6 (Continued)

Test No.	Phases Connected	Average Penetration Resistance C, psi	Design Deflection Coefficient $\delta/H, 2\delta/d$	Wheel Load H, lb		Average Pull, P, lb		Sinkage z, in.	Average Torque M, ft-lb	Full Coefficient		Sinkage Coefficient z/d	Toque Coefficient M/M <sub>r</sub>	$\frac{\text{Chd} \cdot \left(\frac{d}{H}\right)^{1/2}}{W} \cdot \frac{1}{1 + \frac{b}{2d}}$	$\frac{\text{Chd} \cdot \left(\frac{d}{H}\right)^{1/2}}{W} \cdot \left(\frac{1 - \frac{b}{H}}{1 + \frac{b}{2d}}\right)^2$	$\frac{\text{Ch}^{1/2} d^{3/2}}{W} \cdot \left(1 + \frac{4b}{d}\right)^4$	$\frac{\text{Ch} \cdot W}{W}$
				Design	Test	P <sub>1</sub>	P <sub>2</sub>			P <sub>1</sub> /H	P <sub>2</sub> /H						
6.00-16, 2-PR (Continued)																	
331C	5	20	0.35	225	229	171	--	0.28	199	0.747	--	0.010	0.791	9.61	8.60	84.51	4.90
332C	5	37	0.1299	225	232	330	--	0.00	369	1.422	--	0.000	1.449	17.55	15.71	154.26	8.90
333C	5	53	0.1299	225	231	351	--	0.00	396	1.519	--	0.000	1.561	25.25	22.60	222.07	12.93
334C	5	20	0.1302	455	439	159	--	0.74	216	0.362	--	0.026	0.447	5.03	4.50	44.38	4.29
335C	5	37	0.1302	455	448	324	--	0.20	363	0.723	--	0.007	0.736	9.11	8.16	80.45	4.13
336C	5	53	0.1302	455	451	435	--	0.16	497	0.955	--	0.006	1.001	12.97	11.61	114.48	5.91
337C	5	21	0.1302	670	634	136	--	1.20	332	0.215	--	0.012	0.332	3.65	3.27	32.87	1.73
338C	5	36	0.1302	670	664	343	--	0.51	424	0.517	--	0.018	0.580	7.98	7.26	72.81	2.82
339C	5	50	0.1302	670	666	417	--	0.44	497	0.626	--	0.015	0.678	8.28	7.42	73.13	3.96
340C	4	21	0.1307	890	834	29	--	2.44	333	0.035	--	0.086	0.362	2.18	1.96	24.63	1.43
341C	1	39	0.1307	890	892	286	--	0.85	390	0.321	--	0.030	0.397	4.43	4.13	42.82	2.16
342C	5	52	0.1307	890	863	439	--	0.40	531	0.509	--	0.014	0.558	6.66	5.96	59.02	3.42
6.00-16, Solid																	
331C	5	22	0.010	225	213	63	--	1.07	98	0.296	--	0.038	0.397	2.01	1.79	14.31	0.19
332C	3	53	0.010	225	229	116	--	0.49	152	0.507	--	0.018	0.573	4.51	4.01	40.88	0.43
331C	5	10	0.025	455	438	149	--	1.04	233	0.340	--	0.037	0.444	2.81	2.50	25.40	0.28
332C	5	22	0.025	455	427	141	--	2.00	160	0.095	--	0.072	0.141	1.59	1.41	14.56	0.16
334C	5	53	0.025	455	458	190	--	0.82	269	0.415	--	0.029	0.509	3.57	3.17	31.07	0.35
9.00-14, 2-PR																	
297C	5	17	0.15	225	218	99	--	0.16	119	0.454	--	0.016	0.431	7.03	6.13	55.62	2.07
304C	5	34	0.0674	225	222	142	--	0.00	153	0.640	--	0.000	0.607	12.99	11.33	102.80	3.83
305C	5	54	0.0674	225	241	284	--	0.00	303	1.178	--	0.000	1.107	20.19	17.61	159.80	5.96
303C	5	17	0.0678	455	431	85	--	1.50	169	0.197	--	0.053	0.344	3.13	2.84	28.45	1.06
305C	5	51	0.0678	455	443	261	--	0.00	293	0.689	--	0.000	0.580	10.46	9.12	83.03	3.09
306C	5	16	0.0678	455	449	163	--	0.28	198	0.363	--	0.010	0.387	6.47	5.65	51.40	1.91
306C	2	32	0.0676	670	623	17	--	2.71	217	0.027	--	0.095	0.304	2.35	2.05	20.18	0.68
306C	5	37	0.0676	670	643	193	--	1.20	274	0.300	--	0.046	0.372	3.72	3.29	33.81	1.23
313C	5	50	0.0676	670	682	400	--	0.64	480	0.613	--	0.023	0.643	7.99	7.09	24.91	2.30
307C	5	31	0.0684	890	851	161	--	1.61	301	0.189	--	0.056	0.308	2.93	2.67	26.88	0.87
418C	5	52	0.0684	890	878	318	--	1.05	467	0.362	--	0.037	0.462	5.17	4.77	43.70	1.42
299C	5	16	0.121	455	425	110	--	1.23	186	0.259	--	0.044	0.395	4.38	3.82	36.36	1.97
310C	5	34	0.121	455	433	267	--	0.08	293	0.617	--	0.003	0.610	9.13	7.97	75.84	4.11
312C	3	57	0.121	455	441	134	--	0.10	471	0.984	--	0.004	0.963	15.04	13.12	124.83	6.77
300C	1	16	0.1123	890	817	-71	--	4.07	261	-0.087	--	0.144	0.287	2.30	2.00	19.10	0.96
311C	5	35	0.1123	890	862	260	--	0.88	361	0.302	--	0.031	0.376	4.76	4.15	39.60	2.04
419C	5	51	0.1123	890	887	404	--	0.41	511	0.555	--	0.014	0.517	6.74	5.88	56.07	2.89
314C	5	36	0.1532	225	241	293	--	0.32	309	1.216	--	0.011	1.190	20.21	17.65	188.74	11.76
315C	5	55	0.1532	225	227	326	--	0.34	357	1.436	--	0.012	1.460	32.78	28.62	306.14	19.07
417C	5	25	0.1532	225	233	218	--	0.22	215	0.936	--	0.008	0.976	14.52	12.68	135.57	8.14
302C	1	40	0.1558	455	440	432	--	0.02	468	0.628	--	0.001	0.574	7.04	6.14	43.20	2.44
408C	5	23	0.1558	455	449	292	--	0.24	329	0.650	--	0.009	0.677	7.04	6.14	43.20	2.44
410C	5	51	0.1558	455	447	186	--	0.67	334	1.087	--	0.009	1.104	25.67	22.62	245.92	14.52
422C	5	42	0.1557	670	618	223	--	0.24	303	0.384	--	0.024	0.384	4.67	4.13	43.46	1.92
411C	4	52	0.1557	670	662	365	--	0.30	698	0.884	--	0.011	0.918	10.81	9.43	100.56	5.95

(3 of 5 sheets)

Table 6 (Continued)

Test No.	Pastes Completed	Average Penetration Resistance C, psi	Design Deflection Coefficient $\frac{\delta}{h}$	Wheel Load W, lb		Average Pull, lb P	Sinkage z, in.	Average Torque M, ft-lb	Pull Coefficient $\frac{P}{M}$	Sinkage Coefficient $\frac{z}{d}$	Torque Coefficient $\frac{M}{Wd}$	$\frac{Cb_d}{M} \cdot \left(\frac{\delta}{h}\right)^{1/2}$	$\frac{Cb_d}{M} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \left(\frac{1}{1 + \frac{b}{2d}}\right)^2$	$\frac{Cb_d}{M} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \left(\frac{1}{1 + \frac{b}{2d}}\right)^2 \cdot \left(\frac{1}{1 + \frac{b}{2d}}\right)^4$	$\frac{Cb_d}{M} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \left(\frac{1}{1 + \frac{b}{2d}}\right)^2 \cdot \left(\frac{1}{1 + \frac{b}{2d}}\right)^4 \cdot \left(\frac{1}{1 + \frac{b}{2d}}\right)^4$
				Design	Ave Test										
9.00-14, 2-PR (Continued)															
L12C	5	39	0.35	0.1567	670	683	364	--	0.28	0.010	0.596	8.23	7.18	28.73	76.58
L13C	5	32	0.1576	890	884	371	--	0.30	0.011	0.467	6.09	5.32	21.28	57.08	3.09
L15C	5	56	0.1576	890	866	639	--	0.53	0.019	0.769	8.93	7.80	31.19	83.86	4.53
L16C	5	23	0.1576	890	862	123	--	1.20	0.143	0.307	3.67	3.22	12.67	34.52	1.87
15-C	5	45	0.25	0.1124	670	686	--	0.49	--	0.480	7.67	6.69	23.79	63.86	3.33
25-C	5	50	0.1127	1134	1095	--	0.28	0.88	0.217	0.031	5.38	4.69	16.86	44.86	2.26
27-C	5	19	0.1123	795	765	--	1.61	330	0.057	0.388	2.90	2.52	9.01	24.18	1.86
28-CA	4	37	0.1141	1840	1778	--	3.09	480	-0.059	0.108	2.43	2.18	7.70	20.89	1.04
28-CB	4	43	0.1141	1840	1804	--	1	529	0.001	0.092	2.84	2.61	8.81	23.93	1.19
39-C	5	16	0.1106	117	128	--	0.12	161	0.930	0.004	1.140	14.25	12.44	44.24	118.22
1.75-26															
L29C	5	40	0.15	0.0149	100	107	47	--	0.46	0.016	0.433	7.02	6.81	24.33	82.44
L30C	5	40	0.15	0.0149	225	214	58	--	1.14	0.040	0.389	3.61	3.50	12.51	41.82
16x6.50-8, 2-PR															
601C	5	18	0.15	0.0633	225	214	32	27	0.87	0.054	0.324	3.36	2.81	10.03	22.18
605C	5	12	0.0633	225	216	85	81	67	0.304	0.375	0.167	7.78	6.49	23.18	51.29
608C	5	10	0.0633	225	214	83	78	65	0.388	0.364	0.167	7.13	6.24	22.28	49.30
619C	5	18	0.0633	225	204	19	13	39	0.093	0.084	0.294	3.53	2.94	10.52	23.27
622C	3	19	0.0651	350	325	8	8	52	-0.025	-0.025	0.244	2.38	1.99	7.10	15.92
648C	3	17	0.25	0.1046	225	203	29	24	0.143	0.118	0.370	4.26	3.54	12.60	28.66
651C	5	36	0.1046	225	233	93	90	80	0.399	0.386	0.548	7.86	6.54	23.25	52.87
660C	5	39	0.1068	455	459	75	73	95	0.163	0.159	0.326	4.05	3.38	12.01	27.85
667C	5	39	0.1431	225	219	124	120	91	0.546	0.548	0.686	10.57	8.77	35.10	76.41
670C	5	39	0.1431	225	219	135	131	99	0.589	0.003	0.747	10.57	8.77	35.10	76.41
682C	5	37	0.1431	225	223	120	115	96	0.516	0.000	0.711	9.85	8.17	32.70	71.19
686C	5	41	0.1476	455	453	130	127	111	0.280	0.037	0.397	5.49	4.57	18.29	41.23
699C	5	42	0.1476	455	449	153	150	124	0.334	0.010	0.448	5.67	4.72	18.90	42.61
16x11.50-6, 2-PR															
617C	5	25	0.15	0.0915	225	214	107	106	0.500	0.495	0.653	8.69	6.57	23.49	54.75
639C	5	15	0.0915	225	205	36	32	53	0.176	0.156	0.377	5.81	4.39	15.69	36.58
640C	5	38	0.0915	225	218	143	139	122	0.656	0.638	0.815	12.96	8.14	35.05	81.70
645C	5	34	0.0915	225	235	136	131	118	0.573	0.557	0.731	10.76	8.14	29.09	67.81
659C	2	17	0.0918	455	444	19	14	101	0.043	0.032	0.386	2.93	2.22	7.96	18.81
660C	4	21	0.0918	455	440	58	58	143	0.132	0.132	0.358	3.65	2.78	9.93	23.45
662C	5	27	0.0918	455	458	128	124	154	0.279	0.271	0.477	4.51	3.43	12.26	28.97
612C	3	23	0.0942	600	572	32	31	102	0.056	0.054	0.249	3.13	2.39	8.55	20.53
644C	4	34	0.25	0.1505	225	243	190	158	0.782	0.757	0.992	13.23	9.97	35.16	93.78
647C	4	25	0.25	0.1505	225	223	99	93	0.444	0.413	0.636	8.43	6.39	22.73	60.11

(Continued)

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Table 6 (Continued)

Pastes Com- pleted	Test No.	Average Penetration C, psi	Design Deflection Coefficient δ/h	Wheel Load		Average		Sinkage z, in.	Average Torque M, ft-lb	Pull Coefficient P/M	Sinkage Coefficient z/d	Torque Coefficient M/Mr	$\frac{Qd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2}$	$\frac{Qd}{W} \cdot \left(\frac{1}{1-h}\right)^2$	$Cb \frac{1}{2} d^{3/2}$	$Cb \cdot \left(\frac{1}{1-h}\right)^2 \cdot \left(1 + \frac{12}{d}\right)$	Ch W
				W, lb	Design	Pull, lb	P										
9.50-14, 2-PR (Continued)																	
5	L29C	39	0.35	0.1567	670	652	364	--	414	0.558	--	0.010	8.23	7.18	28.73	76.58	44.53
5	L43C	39	0.1576	0.1576	890	884	371	--	448	0.420	--	0.011	6.09	5.32	21.28	57.08	3.09
5	L45C	56	0.1576	0.1576	890	866	639	--	723	0.738	--	0.019	8.93	7.80	31.19	83.66	4.53
5	L46C	23	0.1576	0.1576	890	862	123	--	287	0.143	--	0.042	3.67	3.22	12.67	34.52	1.87
5	L5-C	45	0.25	0.1124	670	686	--	329	410	--	0.160	0.017	7.67	6.69	23.79	63.86	3.33
5	L24-C	50	0.1127	0.1127	1134	1095	--	238	391	--	0.217	0.031	4.69	4.69	14.86	44.86	2.36
5	L37-C	19	0.1123	0.1123	795	765	--	149	330	--	0.195	0.057	2.90	2.53	9.01	24.18	1.26
4	L38-CA	37	0.1141	0.1141	1840	1778	--	-105	480	--	-0.059	0.108	2.40	2.16	7.70	20.89	1.04
4	L38-CB	43	0.1141	0.1141	1840	1804	--	1	529	--	0.001	0.092	2.48	2.18	8.81	23.93	1.19
5	L39-C	16	0.1106	0.1106	117	128	--	119	161	--	0.930	0.004	14.25	12.44	44.24	118.22	6.53
1.75-26																	
5	L29C	40	0.15	0.0149	100	107	47	--	54	0.439	--	0.016	7.02	6.81	24.33	82.44	0.82
5	L30C	40	0.15	0.0149	225	214	58	--	97	0.271	--	0.040	3.61	3.50	12.51	41.82	0.46
16x6.50-8, 2-PR																	
5	601C	18	0.15	0.0633	225	214	32	27	45	0.150	0.126	0.054	3.36	2.81	10.03	22.18	0.91
5	605C	42	0.0633	0.0633	225	216	85	81	67	0.394	0.375	0.011	7.78	6.49	23.18	51.29	2.10
5	608C	10	0.0633	0.0633	225	214	83	78	65	0.388	0.364	0.002	7.13	6.24	22.28	49.30	2.02
5	619C	18	0.0633	0.0633	225	204	19	13	39	0.093	0.064	0.071	2.94	2.94	10.52	23.27	0.95
3	622C	19	0.0651	0.0651	350	325	-8	-8	52	-0.025	-0.025	0.097	2.38	1.99	7.10	15.92	0.67
3	648C	17	0.25	0.1046	225	203	29	24	47	0.143	0.118	0.057	4.26	3.54	12.60	28.66	1.82
5	650C	36	0.1046	0.1046	225	233	93	90	80	0.399	0.366	0.008	7.86	6.54	23.25	52.87	3.37
5	651C	36	0.1068	0.1068	455	459	75	73	95	0.163	0.159	0.039	4.05	3.38	12.01	27.85	1.59
5	640C	39	0.35	0.1431	225	219	124	120	91	0.565	0.548	0.000	10.57	8.77	35.10	76.41	5.75
5	607C	39	0.1431	0.1431	225	219	135	131	92	0.389	0.369	0.003	10.57	8.77	35.10	76.41	5.75
5	652C	37	0.1431	0.1431	225	223	120	115	95	0.516	0.500	0.000	9.85	8.17	32.70	71.19	5.36
5	606C	41	0.1476	0.1476	455	453	130	127	111	0.280	0.260	0.037	5.49	4.57	18.29	41.23	2.74
5	609C	42	0.1476	0.1476	455	449	153	150	124	0.334	0.314	0.010	5.67	4.72	18.90	42.61	2.83
16x11.50-6, 2-PR																	
5	617C	25	0.15	0.0915	225	211	107	106	96	0.500	0.495	0.009	8.69	6.57	23.49	54.75	2.98
5	639C	15	0.0915	0.0915	225	205	36	32	53	0.176	0.156	0.054	5.81	4.39	15.69	36.58	1.99
5	640C	38	0.0915	0.0915	225	218	143	139	122	0.656	0.638	0.002	12.96	9.81	35.05	81.70	4.45
5	645C	34	0.0915	0.0915	225	235	136	131	118	0.578	0.557	0.000	10.76	8.14	29.09	67.81	3.69
2	659C	17	0.0918	0.0918	455	444	19	14	101	0.043	0.032	0.102	2.93	2.22	7.96	18.81	0.89
4	660C	21	0.0918	0.0918	455	440	58	58	111	0.132	0.132	0.081	3.65	2.78	9.93	23.45	1.12
5	662C	27	0.0918	0.0918	455	458	128	124	154	0.272	0.271	0.019	4.51	3.43	12.26	28.97	1.38
3	612C	23	0.0942	0.0942	600	572	32	31	102	0.055	0.054	0.063	8.55	6.55	20.53	48.55	0.81
4	644C	34	0.25	0.1505	225	243	190	184	158	0.782	0.757	0.000	13.23	9.97	35.16	93.78	6.94
4	647C	25	0.25	0.1505	225	223	99	92	93	0.444	0.413	0.021	8.45	6.39	22.73	60.11	4.45

(Continued)

(4 of 5 sheets)

Table 6 (Concluded)

[illegible]

Table 7

Single-Wheel Tests in Fat Clay, Towed Point, First Pass (Eleven Pneumatic Tires and One Solid-Rubber Tire)

Test No.	Passes Completed	Average Penetration Resistance $C_u$ , psi	Design Deflection Coefficient		Wheel Load $W$ , lb		Average Towed Force $P$ , lb		Sinkage $z$ , in.	Towed Force Coefficient		Sinkage Coefficient $z/d$	$\frac{C_{d1}}{V} \cdot \left(\frac{\delta}{h}\right)^{1/2}$	$\frac{C_{d1}}{V} \cdot \left(\frac{\delta}{h}\right)^{1/2}$
			$\delta/h$	$\delta/4$	Design	Test	$\frac{P}{W}$	$\frac{P}{W}$						
1.00-7, 2-PR														
363C	5	56	0.15	0.052	100	113	3	0.18	0.027	0.013	11.31	9.85		
368C	5	45		0.0652	100	111	13	0.11	0.117	0.010	9.25	8.06		
371C	3	26		0.0652	100	97	9	0.10	0.093	0.021	6.12	5.33		
369C	4	45		0.0665	225	226	31	0.40	0.137	0.028	4.71	4.10		
383C	5	66		0.0665	225	228	19	0.15	0.083	0.011	6.70	5.83		
373C	3	41		0.0662	340	335	43	0.88	0.188	0.062	2.87	2.49		
380C	5	66		0.0662	340	340	37	0.55	0.109	0.039	4.55	3.95		
375C	3	42		0.0672	455	439	104	1.01	0.237	0.071	2.28	1.98		
385C	3	66		0.0672	455	451	66	0.72	0.146	0.050	3.49	3.03		
1.00-20, 2-PR														
364C	5	46	0.25	0.104	100	117	3	0.00	0.026	0.000	11.54	10.05		
372C	5	26		0.1054	100	103	7	0.00	0.068	0.000	7.41	6.45		
367C	5	62		0.1092	225	217	29	0.00	0.134	0.000	8.43	7.34		
370C	5	44		0.1092	225	229	17	0.25	0.074	0.018	5.67	4.94		
374C	5	42		0.1103	340	330	49	0.42	0.148	0.030	5.78	5.02		
364C	5	66		0.1103	340	340	33	0.22	0.097	0.016	2.54	2.21		
376C	1	37		0.1102	455	436	125	1.16	0.287	0.082	4.35	3.79		
386C	5	65		0.1102	455	446	48	0.44	0.108	0.031	5.35	4.64		
1.00-20, 2-PR														
378C	5	34	0.35	0.1532	225	221	23	0.30	0.104	0.021	5.35	4.66		
387C	5	66		0.1532	225	222	16	0.00	0.072	0.000	10.34	9.01		
379C	3	36		0.1532	340	322	47	0.71	0.208	0.050	3.90	3.40		
388C	5	66		0.1532	340	336	14	0.00	0.042	0.000	6.85	5.96		
377C	1	38		0.1544	455	446	88	0.78	0.197	0.055	2.99	2.60		
389C	5	68		0.1544	455	448	37	0.22	0.083	0.016	5.33	4.64		
1.00-20, 2-PR														
401C	5	48	0.08	0.0190	315	305	17	0.57	0.056	0.020	5.52	5.12		
402C	5	22	0.08	0.0190	315	307	48	1.30	0.156	0.044	2.51	2.33		
1.00-20, 2-PR														
269C	5	20	0.15	0.0336	225	204	12	0.78	0.059	0.028	4.44	4.13		
275C	5	48		0.0336	225	221	5	0.16	0.023	0.006	9.84	9.16		
279C	5	32		0.0336	225	228	11	0.37	0.048	0.013	6.36	5.92		
271C	5	18		0.0342	455	388	99	1.82	0.255	0.065	2.13	1.98		
273C	5	40		0.0342	455	455	32	0.55	0.070	0.020	4.63	4.31		
287C	5	32		0.0342	455	448	57	1.05	0.127	0.037	3.28	3.05		
286C	5	48		0.0341	470	429	61	0.87	0.097	0.031	3.53	3.29		
1.00-20, 2-PR														
270C	5	22	0.25	0.0559	225	204	9	0.16	0.044	0.006	1.19	1.10		
276C	5	52		0.0559	225	228	5	0.00	0.022	0.000	13.08	12.18		
280C	5	33		0.0559	225	225	10	0.18	0.044	0.006	8.41	7.84		
272C	5	19		0.0644	455	377	78	1.69	0.207	0.060	2.95	2.74		
274C	5	48		0.0644	455	450	17	0.08	0.038	0.003	6.24	5.81		
288C	5	33		0.0644	455	447	46	0.83	0.103	0.030	4.32	4.02		
281C	5	47		0.0670	470	445	41	0.72	0.095	0.024	4.40	4.00		
291C	5	40		0.0670	470	464	54	1.20	0.130	0.043	3.55	3.30		
293C	5	54		0.0670	470	437	35	0.42	0.055	0.015	5.00	4.65		
1.00-20, 2-PR														
277C	5	50	0.35	0.0782	225	211	8	0.00	0.038	0.000	15.84	14.76		
283C	5	29		0.0782	225	224	5	0.04	0.021	0.001	8.21	7.66		
289C	5	19		0.0782	225	223	5	0.35	0.021	0.013	5.38	5.09		
278C	5	50		0.0788	455	433	15	0.10	0.035	0.004	7.90	7.35		
284C	5	30		0.0788	455	454	35	0.13	0.077	0.023	4.52	4.21		
295C	5	19		0.0788	455	421	59	1.25	0.140	0.045	3.09	2.87		
282C	5	4		0.0800	470	451	39	0.41	0.040	0.015	4.77	4.44		
298C	5	35		0.0800	470	464	41	0.81	0.092	0.029	3.64	3.39		
294C	5	52		0.0800	470	428	21	0.20	0.033	0.007	5.72	5.32		
285C	5	52		0.0800	470	420	36	0.47	0.052	0.017	5.17	4.81		
1.00-20, 2-PR														
400C	5	43	0.45	0.1009	470	440	36	0.32	0.055	0.011	5.65	5.28		
403C	5	22	0.45	0.1009	470	435	145	1.99	0.228	0.071	2.64	2.50		
1.00-20, 2-PR														
321C	5	20	0.15	0.0559	225	238	14	0.44	0.059	0.011	1.07	1.04		
323C	5	13		0.0559	225	237	3	0.08	0.013	0.003	19.20	17.19		
329C	3	40		0.0559	225	238	5	0.00	0.021	0.001	12.14	10.8		
325C	5	20		0.0565	455	440	12	1.44	0.144	0.051	3.3	3.02		
351C	5	55		0.0565	455	441	15	0.18	0.033	0.006	8.75	7.95		
327C	3	20		0.0564	470	441	140	2.10	0.254	0.074	2.30	2.04		
339C	5	40		0.0564	470	468	75	0.89	0.112	0.031	4.35	3.90		
344C	5	37		0.0564	890	877	136	1.25	0.155	0.044	3.07	2.75		
359C	5	44		0.0564	890	875	100	0.89	0.114	0.031	4.50	4.03		
1.00-20, 2-PR														
322C	5	20	0.25	0.0928	225	243	9	0.18	0.037	0.006	7.66	7.06		
324C	5	61		0.0928	225	234	1	0.10	0.004	0.004	24.28	21.74		
330C	5	40		0.0923	225	237	5	0.08	0.021	0.004	14.50	13.13		
326C	5	19		0.0934	455	444	53	0.94	0.110	0.034	3.39	3.07		
357C	5	51		0.0934	455	460	10	0.12	0.022	0.004	10.34	9.24		
354C	5	50		0.0933	470	462	33	0.12	0.050	0.004	7.05	6.32		
348C	5	22		0.0932	720	688	153	1.42	0.222	0.050	2.97	2.68		
352C	1	50		0.0932	720	716	37	0.32	0.052	0.011	4.53	4.05		

(Continued)

\*  $P$  is towed force plus  $ma$  (mass times acceleration) measured in a programmed-increasing-slip test. See Appendix A for a more detailed explanation.

\*\* Sinkage at the towed point. First-pass data.

Table 7 (Continued)

Test No.	Passes Completed	Average Penetration Resistance $C_p$ , psi	Design Deflection Coefficient		Wheel Load $W$ , lb	Average Towed Force, lb	Sinkage $z$ , in.	Towed Force Coefficient $\frac{F}{W}$	Sinkage Coefficient $\frac{z}{d}$	$\frac{Cbd}{W} \cdot \left(\frac{\delta}{b}\right)^{1/2}$	$\frac{Cbd}{W} \cdot \left(\frac{\delta}{b}\right)^{1/2} \cdot \frac{1}{1 + \frac{b}{2d}}$
			$\frac{\delta}{h}$	$\frac{\delta}{2d/4}$	Design	Average Test					
6.00-16, 2-PR (Continued)											
137C	3	21	0.25	0.0932	890	848	248	0.292	0.063	2.32	2.06
W5C	5	37		0.0932	890	893	113	0.90	0.032	3.88	3.48
360C	5	52		0.0932	890	889	59	0.30	0.066	5.48	4.91
331C	5	20	0.35	0.1299	225	240	9	0.14	0.038	9.17	8.21
342C	5	37		0.1299	225	226	6	0.00	0.027	9.00	8.01
355C	5	53		0.1299	225	223	10	0.00	0.045	26.15	23.41
338C	3	20		0.1302	455	457	34	0.38	0.074	4.83	4.32
343C	5	27		0.1302	455	448	15	0.00	0.033	9.11	8.16
356C	5	53		0.1302	455	447	15	0.00	0.034	13.08	11.72
341C	5	36		0.1302	670	672	28	0.30	0.042	5.91	5.29
358C	5	50		0.1302	670	673	15	0.14	0.022	8.20	7.34
346C	1	39		0.1307	890	878	62	0.36	0.071	4.91	4.40
361C	5	52		0.1307	890	873	40	0.06	0.045	6.58	5.89
6.00-16, Solid											
393C	5	22	0.010	0.0036	225	214	29	0.87	0.136	2.00	1.78
395C	3	53	0.010	0.0036	225	229	14	0.50	0.061	4.41	4.01
391C	5	40	0.003	0.0093	455	442	56	0.84	0.127	2.79	2.48
392C	5	22		0.0093	455	429	102	1.58	0.238	1.58	1.40
394C	5	53		0.0093	455	456	51	0.74	0.112	3.58	3.18
9.00-14, 2-PR											
297C	5	17	0.15	0.0674	225	227	9	0.10	0.040	6.75	5.89
304C		32		0.0674	225	231	4	0.00	0.017	12.48	10.89
308C		54		0.0674	225	238	3	0.00	0.013	20.44	17.84
298C		17		0.0678	455	434	70	1.10	0.161	3.56	3.10
303C		51		0.0678	455	444	12	0.00	0.027	10.43	9.10
305C		32		0.0678	455	459	15	0.04	0.033	6.33	5.52
301C		16		0.0676	670	621	151	2.53	0.308	2.35	2.05
306C		30		0.0676	670	653	72	1.05	0.110	4.20	3.67
313C		57		0.0676	670	652	41	0.43	0.063	7.99	6.98
307C		11		0.0684	890	866	118	1.29	0.136	3.30	2.88
418C		52		0.0684	890	882	78	0.70	0.088	5.44	4.75
299C		16	0.25	0.1121	455	431	55	0.75	0.128	4.32	3.77
310C		34		0.1121	455	436	11	0.00	0.025	9.07	7.91
312C		57		0.1121	455	441	15	0.00	0.034	15.04	13.12
300C	3	16		0.1123	890	817	310	3.10	0.379	2.30	2.00
311C	5	35		0.1123	890	867	80	0.49	0.092	4.73	4.13
419C	5	51		0.1123	890	886	42	0.00	0.047	6.75	5.89
314C		36	0.35	0.1562	225	243	6	0.00	0.025	20.04	17.50
414C		55		0.1562	225	225	14	0.00	0.062	33.07	28.88
417C		25		0.1562	225	233	11	0.00	0.047	14.52	12.68
390C	1	40		0.1568	455	451	19	0.00	0.042	12.18	10.63
408C	5	23		0.1568	455	449	19	0.00	0.042	7.04	6.14
410C	5	51		0.1568	455	442	10	0.00	0.023	15.75	13.93
409C	5	22		0.1567	670	646	53	0.10	0.082	4.79	4.09
411C	4	52		0.1567	670	658	14	0.00	0.021	10.86	9.49
412C	5	39		0.1567	670	658	20	0.00	0.036	8.16	7.12
413C	5	39		0.1576	890	883	36	0.00	0.041	6.10	5.32
415C	5	50		0.1576	890	864	28	0.20	0.032	8.95	7.81
416C	5	23		0.1576	890	880	112	0.55	0.127	3.61	3.15
1.75-26											
429C	5	40	0.15	0.0149	100	108	6	0.46	0.056	0.95	0.74
430C	5	40	0.15	0.0149	225	213	9	0.90	0.130	3.63	3.52
11.00-20, 12-PR											
1	1*	57	0.173	0.0756	4500†	4500	--	--	0.233	2.5	2.2
1A		44	0.173	0.0756	4500	4500	--	--	0.257	1.9	1.7
2		44	0.245	0.1075	4500	4500	--	--	0.245	2.3	2.0
2A		43	0.245	0.1075	4500	4500	--	--	0.223	2.2	1.9
3		50	0.554	0.2422	4500	4500	--	--	0.132	3.9	3.4
3A		44	0.554	0.2422	4500	4500	--	--	0.132	3.4	3.0
4		45	0.444	0.1941	4500	4500	--	--	0.180	3.1	2.7
4A		47	0.444	0.1941	4500	4500	--	--	0.144	3.3	2.9
4B		42	0.444	0.1941	4500	4500	--	--	0.201	2.9	2.5
5		45	0.125	0.0546	3000	3000	--	--	0.231	2.5	2.2
5A		48	0.125	0.0546	3000	3000	--	--	0.216	2.7	2.4
6		42	0.191	0.0848	3000	3000	--	--	0.217	2.9	2.5
7		41	0.304	0.1329	3000	3000	--	--	0.132	3.5	3.1
8		43	0.235	0.1027	3000	3000	--	--	0.161	3.2	2.8
8A		45	0.235	0.1027	3000	3000	--	--	0.136	3.4	3.0
9		44	0.055	0.0240	1500	1500	--	--	0.120	4.2	3.8
10		44	0.077	0.0424	1500	1500	--	--	0.107	4.3	3.8
11		43	0.131	0.0573	1500	1500	--	--	0.085	4.9	4.3

(Continued)

† Only first pass data are available for the 11.00-20, 12-PR tire.

\*\* The 11.00-20, 12-PR tire was loaded by deadweight, so that test load very nearly equaled design load.

(2 of 3 sheets)

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Table 7 (Continued)

Test No.	Passes Completed	Average Penetration Resistance	Design Deflection Coefficient	Wheel Load	Average Towed Force		Sinkage z, in.	Towed Force Coefficient		Sinkage Coefficient z/d	$\frac{C}{V} \cdot \left(\frac{d}{z}\right)^{1/2}$	$\frac{1}{1 + \frac{C}{V}}$		
		C, psi	d/h	W, lb	Test	Test		F/V	F/W					
16x6.50-8, 2-PR														
601C	5	18	0.15	0.0633	225	212	29	34	0.67	0.137	0.160	0.042	3.40	2.83
605C	5	42	↓	0.0633	225	222	9	10	0.06	0.041	0.045	0.004	7.57	6.32
608C	5	40	↓	0.0633	225	219	10	12	0.00	0.046	0.055	0.000	7.30	6.09
649C	3	18	↓	0.0633	225	212	32	38	0.88	0.151	0.179	0.055	3.40	2.83
602C	3	19	↓	0.0651	350	329	65	65	1.24	0.198	0.198	0.076	2.35	1.96
648C	3	17	0.25	0.1046	225	208	19	28	0.39	0.091	0.135	0.03	4.16	3.46
650C	5	36	↓	0.1046	225	235	10	12	0.02	0.043	0.051	0.004	7.79	6.48
651C	2	36	↓	0.1068	455	462	44	46	0.53	0.095	0.100	0	4.02	3.36
604C	5	39	0.35	0.1431	225	220	6	8	0.00	0.027	0.036	0.00	10.52	8.73
607C	↓	39	↓	0.1431	225	218	8	9	0.00	0.037	0.041	0.000	10.62	8.81
652C	↓	37	↓	0.1431	225	225	13	15	0.00	0.058	0.067	0.010	9.76	8.10
606C	↓	41	↓	0.1476	455	457	25	28	0.20	0.095	0.061	0.013	5.44	4.53
609C	↓	42	↓	0.1476	455	446	20	21	0.16	0.045	0.047	0.010	5.71	4.76
16x11.50-6, 2-PR														
617C	5	25	0.15	0.0915	225	211	9	10	0.00	0.043	0.047	0.000	8.81	6.67
639C	5	16	↓	0.0915	225	206	24	29	0.56	0.117	0.141	0.032	5.78	4.37
640C	5	38	↓	0.0915	225	220	9	10	0.00	0.041	0.045	0.005	12.85	9.72
645C	5	34	↓	0.0915	225	240	7	10	0.00	0.029	0.042	0.000	10.54	7.97
659C	2	17	↓	0.0918	455	446	100	105	1.50	0.224	0.235	0.085	2.91	2.22
660C	4	21	↓	0.0918	455	440	61	63	1.31	0.139	0.113	0.074	3.65	2.78
662C	5	27	↓	0.0918	455	455	42	44	0.64	0.092	0.097	0.036	4.54	3.45
612C	4	23	↓	0.0942	600	575	76	90	0.85	0.132	0.157	0.047	3.12	2.38
644C	4	34	0.25	0.1505	225	243	10	14	0.00	0.041	0.058	0.000	13.23	9.97
647C	4	20	0.25	0.1505	225	226	8	12	0.24	0.035	0.053	0.014	8.37	6.31
643C	3	19	0.35	0.2101	225	218	20	21	0.00	0.092	0.096	0.000	9.65	7.26
610C	5	46	↓	0.2114	455	462	22	25	0.04	0.048	0.054	0.002	11.16	8.41
611C	5	22	↓	0.2114	455	453	25	27	0.00	0.055	0.060	0.000	5.44	4.10
642C	1	18	↓	0.2114	455	444	40	44	0.20	0.090	0.099	0.012	4.54	3.42
661C	4	24	↓	0.2114	455	445	26	30	0.00	0.057	0.066	0.000	5.91	4.46
16x15.00-6, 2-PR														
622C	5	32	0.08	0.0486	225	222	9	9	0.12	0.041	0.041	0.007	10.96	7.66
630C	5	32	↓	0.0486	225	219	9	11	0.16	0.041	0.050	0.009	11.11	7.77
631C	3	16	↓	0.0486	225	205	20	19	0.99	0.098	0.093	0.056	5.93	4.15
653C	4	21	↓	0.0486	225	207	12	14	0.14	0.058	0.068	0.008	7.71	5.39
655C	4	21	↓	0.0486	225	210	12	14	0.30	0.057	0.067	0.017	7.60	5.32
618C	3	27	0.15	0.0879	225	219	5	5	0.00	0.023	0.023	0.000	12.61	8.78
629C	2	31	↓	0.0879	225	220	12	12	0.12	0.055	0.055	0.007	14.22	10.03
632C	5	17	↓	0.0879	225	218	14	15	0.16	0.064	0.069	0.009	7.98	5.55
634C	5	32	↓	0.0906	455	476	26	29	0.31	0.055	0.061	0.018	6.99	4.89
646C	2	17	↓	0.0906	455	457	78	86	0.99	0.171	0.188	0.056	3.87	2.70
638C	3	16	↓	0.0906	455	441	78	82	0.86	0.177	0.185	0.049	3.77	2.64
621C	5	29	0.25	0.1439	225	215	5	6	0.00	0.023	0.028	0.000	17.37	11.99
623C	5	27	↓	0.1474	455	461	14	16	0.04	0.030	0.035	0.002	7.74	5.38
624C	3	28	↓	0.1474	455	447	13	14	0.08	0.029	0.031	0.005	8.27	5.76
627C	5	30	↓	0.1474	455	459	12	15	0.00	0.026	0.033	0.000	8.63	6.01
628C	3	18	↓	0.1474	455	446	36	38	0.24	0.081	0.085	0.014	5.33	3.71
633C	5	31	↓	0.1474	455	481	20	21	0.08	0.042	0.044	0.005	8.51	5.92
635C	3	16	↓	0.1474	455	467	66	68	0.54	0.141	0.146	0.031	4.53	3.15
620C	2	20	0.35	0.2027	225	221	12	12	0.00	0.054	0.054	0.000	17.75	12.22
637C	4	16	↓	0.2056	455	452	36	38	0.16	0.080	0.084	0.009	5.48	3.80
654C	5	21	↓	0.2056	455	456	23	24	0.06	0.050	0.053	0.003	7.12	4.94
26x16.00-10, 4-PR														
705C	3	8	0.15	0.0744	315	302	30	39	0.93	0.099	0.129	0.038	4.00	3.00
701C	5	34	0.15	0.0751	890	867	44	54	0.55	0.055	0.062	0.022	6.01	4.52
31x15.50-13, 4-PR														
668C	5	28	0.04	0.0416	225	225	6	8	0.16	0.027	0.036	0.005	15.73	12.57
670C	4	22	↓	0.0416	225	206	4	8	0.27	0.019	0.039	0.009	13.44	10.74
673C	4	32	↓	0.0416	225	230	5	8	0.15	0.022	0.035	0.005	17.59	14.05
664C	5	29	0.15	0.0769	455	469	19	20	0.00	0.041	0.043	0.000	10.65	8.50
665C	4	20	↓	0.0769	455	445	25	30	0.20	0.056	0.067	0.007	7.74	6.18
671C	5	22	↓	0.0769	455	441	10	16	0.15	0.023	0.036	0.005	8.60	6.86
672C	5	33	↓	0.0769	455	462	16	20	0.08	0.035	0.043	0.003	12.31	9.82
667C	5	28	0.25	0.1288	890	871	48	53	0.38	0.055	0.061	0.013	7.15	5.71
674C	5	24	↓	0.1288	890	872	23	31	0.16	0.026	0.036	0.005	6.12	4.89
669C	3	22	↓	0.1291	1200	1196	138	150	0.53	0.119	0.130	0.018	4.27	3.41

### Single-Wheel Tests in Fat Clay, 20 Percent Slip, Design Translational Velocities from 0.5 to 18 Ft/Sec

Test No.	Average Penetration Resistance C, psi	Average Wheel Test Load W, lb	Average Pull P, lb	Average Sinking* z, in.	Average Torque M, ft.-lb	Pull Coefficient P/W	Sinking Coefficient z/d	$\frac{Cbd}{W} \cdot \left(\frac{d}{h}\right)^{1/2}$	Wheel Translational Velocity V <sub>w</sub> , ft./sec	Average Test** V <sub>w</sub>	$\left(\frac{V}{d}\right)^{0.092} \left(\frac{b}{V - \frac{V}{d}}\right)^{0.092}$	$\frac{Cbd}{W} \cdot \left(\frac{d}{h}\right)^{1/2} \cdot \frac{1}{1 + \frac{b}{2d}}$	$\frac{Cbd}{W} \cdot \left(\frac{d}{h}\right)^{1/2} \cdot \frac{1}{1 + \frac{b}{2d}} \cdot \left(\frac{0.1V}{b} \cdot \frac{b}{V - \frac{V}{d}}\right)^{0.092}$	$\frac{Cbd}{W} \cdot \left(\frac{d}{h}\right)^{1/2} \cdot \frac{1}{1 + \frac{b}{2d}} \cdot \left(\frac{0.1V}{b} \cdot \frac{b}{V - \frac{V}{d}}\right)^{0.092}$
9.00-14, 2-PR Tire; Design Deflection Coefficient $\frac{\Delta}{h} = 0.25$														
43	681	149	0.55	195	0.219	0.019	0.019	7.38	4.50	0.57	0.947	6.14	4.93	4.93
46	1019	177	0.86	299	0.174	0.030	0.030	5.32	2.00	1.94	1.059	4.64	3.37	3.37
24	367	154	0.43	201	0.420	0.015	0.015	7.59	9.00	8.68	1.216	5.62	4.52	4.52
44	1002	18	1.76	256	0.024	0.062	0.062	3.70	13.00	12.18	1.255	3.24	3.27	3.27
45	686	257	1.00	289	0.256	0.035	0.035	5.17	2.00	1.94	1.059	4.51	3.87	3.87
48	1095	329	0.49	410	0.480	0.017	0.017	7.67	5.00	4.87	1.153	6.69	6.24	6.24
50	1794	238	2.06	391	0.217	0.031	0.031	5.35	5.00	4.87	1.153	4.69	4.30	4.30
26	1100	34	1.79	471	0.019	0.072	0.072	3.19	2.00	1.89	1.056	2.78	2.38	2.38
19	765	-25	3.35	340	-0.023	0.118	0.118	2.78	5.00	1.95	1.060	2.43	2.08	2.08
37	1778	105	1.61	480	0.195	0.057	0.057	2.90	5.00	4.99	1.156	2.53	2.37	2.37
43	1804	-105	3.09	519	-0.059	0.108	0.108	2.48	5.00	4.88	1.152	2.16	2.02	2.02
41	1848	1	2.62	529	0.001	0.092	0.092	2.84	5.00	4.87	1.152	2.48	2.31	2.31
40	1227	218	0.20	248	0.049	0.007	0.007	14.17	2.00	1.95	1.060	12.36	10.60	10.60
44	325	-306	3.49	340	-0.156	0.122	0.122	2.58	0.50	0.44	0.924	2.25	1.68	1.68
44	340	46	2.01	328	0.037	0.071	0.071	3.84	0.50	0.44	0.923	3.35	2.50	2.50
32-C	325	293	0.02	322	0.902	0.001	0.001	15.72	9.00	8.55	1.215	13.71	13.48	13.48
33-C	340	307	0.04	355	0.903	0.004	0.004	11.92	13.00	11.97	1.253	13.11	13.29	13.29
33-C	340	307	0.04	355	0.903	0.004	0.004	11.92	13.00	11.97	1.253	13.11	13.29	13.29
39-C	324	60	0.12	161	0.330	0.004	0.004	14.25	5.00	4.99	1.157	12.44	11.65	11.65
40-C	324	60	0.43	138	0.185	0.015	0.015	6.09	2.00	1.96	1.060	5.31	4.56	4.56
41-C	510	37	2.23	242	0.037	0.079	0.079	3.65	2.00	1.92	1.059	3.35	2.73	2.73
43-C	614	133	1.62	277	0.217	0.057	0.057	3.81	9.00	8.67	1.216	3.32	3.27	3.27
44-C	750	99	2.14	308	0.132	0.076	0.076	3.12	9.00	8.67	1.216	2.72	2.68	2.68
45-C	422	140	0.88	234	0.332	0.031	0.031	5.23	9.00	8.71	1.217	4.57	4.49	4.49
46-C	846	-112	3.41	335	-0.132	0.110	0.110	2.86	9.00	8.67	1.217	2.29	2.24	2.24
47-C	320	167	0.34	232	0.582	0.012	0.012	7.98	13.00	12.07	1.254	6.96	7.06	7.06
48-C	415	153	0.51	240	0.365	0.018	0.018	5.88	13.00	12.07	1.254	5.14	5.21	5.21
49-C	843	-40	2.75	270	-0.047	0.097	0.097	2.50	9.00	8.59	1.255	1.015	1.015	1.015
50-C	703	49	1.98	257	0.070	0.070	0.070	3.16	13.00	12.05	1.253	2.76	2.80	2.80
51-C	794	-16	2.54	267	-0.020	0.090	0.090	2.86	13.00	12.05	1.256	2.44	2.43	2.43
52-C	442	96	0.80	204	0.217	0.028	0.028	5.26	1.25	1.22	1.016	4.59	3.77	3.77
53-C	799	-13	2.60	235	-0.016	0.092	0.092	2.93	1.25	1.20	1.014	2.55	2.09	2.09
54-C	182	140	0.51	192	0.769	0.018	0.018	13.82	1.25	1.25	1.018	12.06	9.94	9.94
55-C	555	272	0.59	380	0.490	0.021	0.021	1.96	1.25	1.19	1.013	6.95	5.69	5.69
56-C	1160	218	--	467	0.188	--	--	4.16	1.25	1.15	1.010	3.63	2.97	2.97
57-C	1453	-138	3.94	502	-0.095	0.138	0.138	2.45	1.25	1.20	1.013	2.14	1.75	1.75

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# first-pass data.
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\* First-pass data.  
\*\* Test values of  $V_w$  were used in computations involving this variable.

Table 8 (Continued)

Test No.	Average Penetration Resistance C, Psi	Average Wheel Load W, lb	Average Pull P, lb	Sinkage z, in.	Average Torque M, ft-lb	Pull Coefficient P/W	Sinkage Coefficient z/d	Cbd · (d/h) <sup>1/2</sup>	Wheel Translational Velocity V, ft/sec	Average Test Design	$\left(\frac{V}{V_0}\right)^{0.092} \left(\frac{d}{d_0}\right)^{0.14}$	Cbd · (d/h) <sup>1/2</sup> · $\frac{1}{1 + \frac{d}{2h}}$	$\frac{Cbd}{W} \cdot \left(\frac{d}{h}\right)^{1/2} \cdot \left(\frac{V}{V_0}\right)^{0.092} \left(\frac{d}{d_0}\right)^{0.14}$	
4.00-7. 2-PH Tire; Design Deflection Coefficient $\frac{d}{h} = 0.25$														
8-C	43	93	74	0.27	45	0.796	0.019	13.54	13.00	12.75	1.342	1.086	11.80	12.81
9-C	42	472	-18	1.52	70	-0.036	0.107	2.66	13.00	12.55	1.338	1.083	2.31	2.51
10-C	44	341	77	0.96	72	0.226	0.069	3.83	9.00	8.78	1.296	1.048	3.34	3.50
11-C	26	51	45	0.00	26	0.882	0.000	14.85	5.00	4.96	1.231	0.996	12.94	12.88
12-C	28	102	42	0.37	28	0.412	0.026	8.06	2.00	2.01	1.132	0.916	7.02	6.43
13-C	26	266	-78	1.64	40	-0.293	0.116	2.89	0.50	0.48	0.992	0.802	2.52	2.02
34-C	48	92	95	0.08	55	1.033	0.006	15.28	13.00	12.76	1.342	1.086	13.31	14.46
35-C	42	401	51	1.09	77	0.127	0.077	3.12	13.00	12.54	1.338	1.083	2.72	2.94
36-C	40	276	54	0.98	74	0.144	0.069	3.17	9.00	8.82	1.296	1.048	2.76	2.89
37-C	41	78	81	0.08	46	1.038	0.006	15.39	9.00	8.76	1.296	1.049	13.41	14.07
58-C	42	466	14	1.39	73	0.030	0.098	2.69	1.25	1.21	1.079	0.873	2.34	2.05
59-C	43	484	50	1.22	90	0.103	0.086	2.65	5.00	4.90	1.227	0.993	2.31	2.29
60-C	44	425	56	1.04	76	0.132	0.073	3.09	2.00	1.92	1.126	0.911	2.69	2.45
61-C	31	134	50	0.49	42	0.258	0.035	4.71	2.00	2.12	1.137	0.920	4.10	3.77
62-C	33	63	61	0.04	41	0.968	0.003	15.32	2.00	1.99	1.131	0.915	13.34	12.21
63-C	33	205	71	0.40	57	0.346	0.028	4.74	5.00	4.96	1.230	0.995	4.13	4.11
64-C	38	153	62	0.27	45	0.405	0.019	7.29	5.00	4.90	1.229	0.994	6.32	6.31
65-C	36	301	40	0.62	55	0.133	0.044	3.75	1.25	1.24	1.082	0.875	3.26	2.86
66-C	40	162	69	0.24	50	0.426	0.017	7.28	1.25	1.19	1.079	0.873	6.34	5.53
67-C	24	148	8	0.92	38	0.694	0.065	4.76	1.25	1.21	1.080	0.874	4.15	3.62
68-C	25	56	31	0.33	23	0.554	0.024	13.01	1.25	1.24	1.083	0.876	11.33	9.93
69-C	24	304	-38	1.37	66	-0.125	0.097	2.34	2.00	1.93	1.127	0.911	2.04	1.86
70-C	22	175	-9	0.72	44	-0.051	0.051	3.70	2.00	1.98	1.130	0.914	3.23	2.95
71-C	22	206	-33	0.76	31	-0.160	0.054	3.15	1.25	1.23	1.082	0.875	2.74	2.40
72-C	22	185	26	1.07	42	0.141	0.076	3.50	5.00	4.93	1.227	0.994	3.05	3.03
73-C	21	195	29	1.21	45	0.149	0.086	3.17	5.00	4.91	1.224	0.994	2.76	2.75
74-C	22	245	9	1.24	48	0.037	0.088	2.66	9.00	8.83	1.296	1.049	2.31	2.43
75-C	24	135	47	0.35	39	0.348	0.025	5.22	9.00	8.71	1.296	1.049	4.55	4.76
76-C	22	85	40	0.14	28	0.471	0.010	7.58	9.00	8.77	1.296	1.049	6.60	6.93
77-C	34	386	-1	0.94	84	0.140	0.066	2.62	18.00	16.80	1.375	1.112	2.29	2.54
78-C	36	349	62	0.76	79	0.178	0.054	3.06	18.00	17.23	1.378	1.115	2.67	2.97
79-C	40	291	88	0.52	77	0.302	0.037	4.08	18.00	16.92	1.376	1.113	3.55	3.96
80-C	21	72	37	0.10	31	0.244	0.007	8.54	18.00	17.36	1.381	1.117	7.44	8.31
81-C	23	38	40	0.00	29	1.053	0.000	17.63	18.00	18.00	1.386	1.121	15.36	17.22
82-C	23	130	44	0.44	36	0.338	0.031	5.19	18.00	17.20	1.379	1.116	4.92	5.05
83-C	22	74	50	0.14	34	0.616	0.010	8.71	13.00	12.78	1.342	1.036	7.59	8.24
84-C	24	133	57	0.33	44	0.425	0.023	5.30	13.00	12.90	1.343	1.085	4.61	5.01
85-C	21	176	46	0.56	40	0.338	0.040	4.53	13.00	12.86	1.343	1.086	3.95	4.29

Table 9

Single-Wheel Tests in Yuma Sand, 20 Percent Slip, Multipass Data

Test No.		Before-Traffic Penetration Resistance Gradient G, psi/in.		Design		Test Wheel Load						Pull						Pull Coefficient						Average						Basic Prediction Term						$Q(bd)^{3/2}$																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
				Deflection Coefficient h/h	Wheel Load W, lb	Pass			Pass			Pass			Pass			Pass			Pass			Pass			Pass			Pass			Pass			Pass			Pass			Pass																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
						1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1 and 2	1, 2, and 3	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes	Passes

\* In the basic prediction term, the "W" used in the average value of W for the passes indicated.


(Continued)

Table 9 (Continued)

Test No.	Before Traffic		Design		Test Wheel Load			Pull			Pull Coefficient			Average			Basic Prediction Term			$Q(bd)^{3/2}$		
	Penetration Resistance Gradient $G, \text{ psi/in.}$		Deflection Coefficient $\delta/h$	Wheel Load $N, \text{ lb}$	Test Wheel Load			P, lb			P/N			Passes			Passes			Passes		
					1	2	3	1	2	3	1	2	3	1 and 2	1, 2, and 3	Passes	1	2	3	1 and 2	1, 2, and 3	Passes
A68-0067-1	16.1	225	0.25	225	223	224	222	95	52	44	0.426	0.232	0.192	0.329	0.285	18.44	18.60	18.48	18.48	18.52	18.52	18.52
	10.2	670	0.25	670	654	648	646	-26	-50	-48	-0.040	-0.077	-0.074	-0.058	-0.064	4.24	4.25	4.22	4.22	4.23	4.23	4.23
	9.4	890	0.25	890	874	867	--	-147	-120	--	-0.168	-0.138	--	-0.153	--	3.00	--	--	--	--	--	--
	6.2	225	0.35	225	226	222	218	60	46	43	0.265	0.207	0.197	0.236	0.223	9.82	10.00	9.74	9.74	9.82	9.82	9.82
A68-0077-1	3.5	455	0.35	455	428	424	428	-72	-16	6	-0.168	-0.036	0.014	-0.103	-0.084	3.00	2.97	2.98	2.98	2.98	2.98	2.98
	20.2	455	0.35	455	452	450	447	183	89	73	0.405	0.198	0.163	0.301	0.255	16.30	16.34	16.26	16.26	16.26	16.26	16.26
	6.2	225	0.15	225	210	219	224	48	29	27	0.229	0.132	0.121	0.180	0.161	11.30	11.05	11.54	11.54	11.38	11.38	11.38
	4.5	455	0.15	455	436	432	431	-30	-4	-2	-0.069	-0.009	-0.008	-0.039	-0.028	4.33	4.34	4.31	4.31	4.32	4.32	4.32
A68-0092-1	6.6	890	0.15	890	861	854	865	-103	-81	-85	-0.120	-0.055	-0.058	-0.107	-0.104	3.29	3.25	3.28	3.28	3.27	3.27	3.27
	10.1	225	0.25	225	227	228	223	107	75	60	0.471	0.329	0.269	0.400	0.356	28.81	29.46	28.88	28.88	29.07	29.07	29.07
	4.1	455	0.25	455	435	436	443	14	24	36	0.032	0.055	0.081	0.044	0.056	6.27	6.17	6.28	6.28	6.24	6.24	6.24
	6.7	455	0.25	455	451	450	450	99	54	56	0.218	0.120	0.124	0.169	0.154	9.50	9.92	9.86	9.86	9.88	9.88	9.88
A68-0101-1	13.1	225	0.35	225	234	231	230	113	101	90	0.483	0.437	0.391	0.460	0.437	50.84	51.03	50.52	50.52	50.69	50.69	50.69
	13.9	890	0.35	890	874	861	870	289	128	87	0.342	0.149	0.100	0.245	0.197	15.40	15.25	15.29	15.29	15.28	15.28	15.28
	3.8	1286	0.35	1286	1253	1250	1243	-161	71	42	-0.128	0.057	0.034	-0.036	-0.013	2.96	2.98	2.96	2.96	2.96	2.96	2.96
	6.9	273	0.15	273	272	266	274	71	34	31	0.274	0.128	0.113	0.194	0.167	16.74	16.25	16.56	16.56	16.45	16.45	16.45
A68-0101-1	6.6	455	0.15	455	450	449	449	49	10	6	0.109	0.022	0.013	0.066	0.048	9.70	9.70	9.69	9.69	9.69	9.69	9.69
	3.5	455	0.15	455	452	450	449	-26	6	4	-0.062	0.013	0.009	-0.024	-0.013	5.13	5.14	5.12	5.12	5.13	5.13	5.13
	11.6	225	0.25	225	228	229	224	119	94	75	0.522	0.410	0.335	0.466	0.422	52.32	53.49	52.44	52.44	52.79	52.79	52.79
	8.7	455	0.25	455	446	449	441	162	100	72	0.363	0.218	0.161	0.290	0.247	20.35	21.18	20.64	20.64	20.82	20.82	20.82
A68-0111-1	7.1	890	0.25	890	879	883	883	66	-11	-16	0.075	-0.012	-0.018	0.032	0.015	8.86	8.86	8.88	8.88	8.87	8.87	8.87
	4.7	890	0.25	890	887	881	880	-64	-57	35	-0.072	-0.065	-0.040	-0.069	-0.032	5.88	5.88	5.86	5.86	5.87	5.87	5.87
	5.0	455	0.35	455	456	457	454	110	90	97	0.240	0.197	0.214	0.219	0.217	16.19	16.29	16.17	16.17	16.21	16.21	16.21
	11.2	455	0.35	455	460	460	453	206	144	118	0.448	0.313	0.260	0.380	0.340	36.02	36.58	36.02	36.02	36.21	36.21	36.21
A68-0111-1	6.4	455	0.15	455	449	458	455	125	76	72	0.278	0.166	0.158	0.222	0.201	16.28	16.39	16.14	16.14	16.43	16.43	16.43
	5.0	890	0.15	890	852	863	863	68	36	43	0.090	0.042	0.050	0.061	0.057	6.84	6.84	6.88	6.88	6.87	6.87	6.87
	11.9	455	0.25	455	446	466	462	217	179	162	0.466	0.384	0.351	0.495	0.400	49.19	49.62	49.19	49.19	49.33	49.33	49.33
	5.9	1286	0.25	1286	1269	1272	1268	241	161	135	0.190	0.127	0.106	0.198	0.161	9.10	9.10	9.12	9.12	9.12	9.12	9.12
A68-0111-1	12.1	890	0.35	890	899	899	897	336	279	264	0.374	0.310	0.294	0.342	0.326	36.30	36.38	36.30	36.30	36.33	36.33	36.33
	4.0	1020	0.35	1020	1023	1015	1019	198	220	234	0.194	0.217	0.230	0.205	0.213	10.63	10.59	10.58	10.58	10.59	10.59	10.59
	17.5	455	0.15	455	451	459	459	205	193	170	0.455	0.420	0.370	0.438	0.415	53.67	53.67	54.14	54.14	53.99	53.99	53.99
	6.5	1000	0.15	1000	977	975	983	180	131	128	0.184	0.134	0.130	0.159	0.150	8.44	8.44	8.51	8.51	8.49	8.49	8.49
A68-0111-1	3.2	890	0.25	890	863	878	877	152	180	189	0.176	0.205	0.216	0.191	0.199	8.55	8.56	8.62	8.62	8.60	8.60	8.60
	9.8	1230	0.25	1230	1205	1195	1173	388	261	242	0.322	0.218	0.206	0.270	0.249	19.47	19.84	19.54	19.54	19.54	19.54	19.54
	13.1	890	0.35	890	889	891	890	392	315	288	0.441	0.358	0.324	0.399	0.374	48.69	48.80	48.47	48.47	48.38	48.38	48.38
	3.2	1350	0.35	1350	1331	1346	1342	234	297	321	0.176	0.221	0.239	0.198	0.212	7.86	7.88	7.90	7.90	7.90	7.90	7.90

Table 10

Single-Wheel Tests in Yuma Sand, Towed Point, Multitests Data

Test No.	Before-Traffic Penetration Resistance Gradient G, psi/in.	Design Deflection Coefficient W/h	Wheel Load W, lb			Towed Force P, lb			Towed Force Coefficient P <sub>y</sub> /W			Average Towed Force Coefficient			Basic Prediction Term			Q(ba) <sup>3/2</sup> Passes <sup>a</sup>	
			W, lb			P, lb			P <sub>y</sub> /W			Passes			Passes				
			1	2	3	1	2	3	1	2	3	1 and 2	1, 2, and 3	1 and 2	1, 2, and 3	1 and 2	1, 2, and 3		
1-65-0064-1	13.3		152	158	--	2	3	--	0.013	0.019	--	0.016	--	--	72.78	73.24	--	--	72.04
	11.8		141	143	136	5	5	0	0.035	0.014	0.000	0.024	0.024	0.024	71.34	71.10	72.04		
	12.7		239	240	239	5	4	5	0.021	0.017	0.021	0.019	0.019	0.019	71.34	71.10	72.04		
	11.6		237	238	232	6	0	0	0.025	0.000	0.000	0.013	0.008	0.008	71.34	71.10	72.04		
	13.2		648	646	646	19	8	12	0.029	0.012	0.019	0.021	0.020	0.020	71.34	71.10	72.04		
	10.3		839	821	820	43	43	43	0.069	0.052	0.051	0.061	0.058	0.058	71.34	71.10	72.04		
	13.2		821	820	804	57	43	9	0.071	0.063	0.065	0.080	0.080	0.080	71.34	71.10	72.04		
A68-0066-1	13.7	0.15	225	236	226	26	18	24	0.111	0.076	0.106	0.094	0.098	9.14	9.54	9.18	9.30		
	4.2	225	214	211	114	98	86	0.533	0.498	0.408	0.495	0.466	0.466	9.14	9.54	9.18	9.30		
	10.0	0.15	225	246	246	83	102	107	0.240	0.295	0.307	0.267	0.261	9.14	9.54	9.18	9.30		
	16.1	0.25	225	227	230	7	4	3	0.031	0.018	0.013	0.024	0.024	9.14	9.54	9.18	9.30		
	6.2	0.35	225	230	226	30	20	15	0.130	0.088	0.067	0.109	0.095	9.14	9.54	9.18	9.30		
	20.2	0.35	455	472	455	18	16	20	0.040	0.035	0.044	0.037	0.040	9.14	9.54	9.18	9.30		
	4.6	0.35	455	430	431	308	273	--	0.716	0.633	--	0.675	--	9.14	9.54	9.18	9.30		
A68-0077-1	6.2	0.15	225	225	226	27	22	17	0.125	0.098	0.075	0.111	0.099	11.00	11.23	11.31	11.31		
	4.8	0.15	455	451	453	190	158	194	0.419	0.439	0.428	0.429	0.428	11.00	11.23	11.31	11.31		
	10.1	0.25	225	226	231	11	11	8	0.049	0.017	0.035	0.033	0.034	11.00	11.23	11.31	11.31		
	5.7	0.25	455	456	458	67	56	40	0.147	0.122	0.087	0.135	0.119	11.00	11.23	11.31	11.31		
	4.8	0.25	455	460	459	105	69	53	0.228	0.190	0.116	0.195	0.165	11.00	11.23	11.31	11.31		
	13.1	0.35	225	234	230	16	11	13	0.068	0.048	0.056	0.058	0.057	11.00	11.23	11.31	11.31		
	13.9	0.35	890	881	880	73	74	60	0.083	0.084	0.068	0.083	0.078	11.00	11.23	11.31	11.31		
A68-0092-1	6.9	0.15	273	271	279	29	22	17	0.104	0.081	0.061	0.093	0.082	16.43	16.20	16.12	16.12		
	6.6	0.15	455	459	459	--	77	69	--	0.168	0.150	--	--	16.43	16.20	16.12	16.12		
	11.6	0.25	225	229	225	7	8	9	0.031	0.035	0.040	0.033	0.035	16.43	16.20	16.12	16.12		
	8.7	0.25	455	448	442	32	33	26	0.071	0.071	0.071	0.071	0.071	16.43	16.20	16.12	16.12		
	11.2	0.35	455	459	453	19	25	22	0.041	0.041	0.041	0.041	0.041	16.43	16.20	16.12	16.12		
	5.0	0.35	455	467	459	55	36	24	0.118	0.118	0.092	0.111	0.092	16.43	16.20	16.12	16.12		
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--		
A68-0101-1	6.4	0.15	455	466	463	36	22	15	0.078	0.047	0.033	0.063	0.053	16.40	16.25	16.17	16.17		
	5.0	0.15	890	865	869	176	137	110	0.203	0.156	0.127	0.180	0.162	16.40	16.25	16.17	16.17		
	11.9	0.25	455	467	468	13	16	13	0.028	0.024	0.028	0.031	0.030	16.40	16.25	16.17	16.17		
	5.7	0.25	1286	1281	1279	162	113	85	0.186	0.088	0.066	0.107	0.096	16.40	16.25	16.17	16.17		
	13.1	0.35	890	896	899	92	80	81	0.109	0.089	0.077	0.133	0.114	16.40	16.25	16.17	16.17		
	4.0	0.35	1020	1036	1031	161	114	80	0.135	0.111	0.077	0.133	0.114	16.40	16.25	16.17	16.17		
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--		
A68-0106-1	6.5	0.15	1000	989	988	--	92	67	--	0.093	0.068	--	--	9.39	9.39	--	--	--	
	3.2	0.25	890	--	890	--	--	40	--	--	0.045	--	--	--	--	--	--	--	
	9.8	0.25	1205	1205	1191	71	62	45	0.059	0.051	0.038	0.049	0.042	9.39	9.39	--	--	--	
	13.1	0.35	890	887	885	39	41	31	0.044	0.046	0.034	0.045	0.042	9.39	9.39	--	--	--	
	3.2	0.35	1350	1361	1366	--	134	94	--	0.091	0.069	--	--	9.39	9.39	--	--	--	
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	
	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	

\* In the basic prediction term, the "W" used is the average value of W for the passes indicated.

Table 11  
Laboratory Tests with 4x4 Vehicles in Yuma Sand, Standard Four-Wheel-Drive Vehicles,  
20 Percent Slip, First Pass

Test No.	Penetration Resistance Gradient, * psi/in.			Design Deflection Coefficient s/h	Design Load W, lb		Total Pull P, lb	Pull Coefficient P/W	Basic Prediction Term	
	G <sub>b</sub>	G'	G		Total	Per Wheel			$\frac{G(bd)^{3/2}}{W^{1/2}}$	$\frac{s}{b}$
M151, 1/4-Ton; 7.00-16, 6-PR Tires (b = 7.5 in., d = 27.7 in.)										
233A	5.3	5.3	4.6	0.15	3560	890	-65	-0.018		2.3
234A	8.3	9.0	7.8				115	0.032		3.9
235A	12.6	13.3	11.5				240	0.067		5.8
236A	16.0	17.0	14.6				385	0.108		7.4
237A	19.4	20.3	17.5				585	0.164		8.8
238A	16.0	16.7	14.4				420	0.118		7.3
239A	5.7	6.0	5.2	0.25			55	0.015		4.4
240A	8.6	9.0	7.8				245	0.069		6.5
241A	13.1	13.7	11.8				585	0.164		9.9
242A	15.4	16.3	14.1				710	0.199		11.9
243A	16.0	16.7	14.4				795	0.223		12.2
244A	19.1	20.0	17.3				980	0.275		14.6
245A	18.5	20.0	17.3				770	0.216		14.6
246A	6.0	6.5	5.6	0.35			470	0.132		6.6
247A	9.1	9.5	8.2				680	0.191		9.6
248A	13.4	13.7	11.8				840	0.236		13.9
249A	18.6	20.0	17.3				970	0.272		20.4
250A	19.6	19.8	17.1				1125	0.316		20.2
251A	20.0	20.7	17.9				1165	0.327		21.1
252A	15.4	16.7	14.4				915	0.257		16.9
253A	17.4	16.7	14.4				1065	0.299		17.0
256A	20.6	20.3	17.5				1230	0.346		20.6
257A	24.3	23.7	20.5				1300	0.365		24.1
M151, 1/4-Ton; 26x16.00-10, 4-PR Tires (b = 16.1 in., d = 24.3 in.)										
280A	8.2	10.3	8.9	0.15	3560	890	445	0.125		11.6
281A	8.7	10.3	8.9				700	0.197		11.6
282A	14.4	13.3	11.5				1010	0.284		15.0
284A	13.1	12.7	11.8				860	0.242		15.4
285A	27.3	26.3	24.5				1160	0.326		31.9
286A	21.5	21.3	18.4				1000	0.281		24.0
288A	1.7	3.0	2.6				-7*	-0.021		3.4
287A	28.8	22.2	19.2	0.25			1290	0.362		41.7
289A	32.1	23.2	20.1				1255	0.353		43.7
291A	22.9	17.7	15.3				1360	0.382		33.3
292A	18.6	15.8	13.7				1190	0.334		29.8
293A	11.5	10.7	9.3				1080	0.303		20.2
294A	1.7	3.3	2.9				120	0.034		6.3
295A	1.8	3.3	2.9	0.35			640	0.180		8.9
296A	9.5	8.7	7.5				1250	0.351		22.8
297A	14.4	13.3	11.5				1520	0.427		35.0
298A	20.3	17.5	15.1				1495	0.420		46.0
299A	24.	23.0	19.9				1570	0.441		60.6
300A	37.1	23.8	20.6				1550	0.435		62.7
M37, 3/4-Ton; 9.00-16, 8-PR Tires (b = 10.2 in., d = 32.8 in.)										
259A	24.5	23.3	20.1	0.15	7240	1810	970	0.134		10.2
260A	17.0	16.7	14.4				705	0.097		7.3
261A	27.3	26.0	22.5				1120	0.155		11.4
262A	21.3	20.0	17.3				865	0.119		8.8
263A	15.6	14.3	12.4				715	0.099		6.3
264A	7.4	9.0	7.8				5	0.001		4.0
265A	4.1	5.7	4.9				-265	-0.037		2.5
266A	17.1	17.0	14.7				890	0.123		7.5
267A	23.5	26.7	23.1	0.25			2005	0.277		19.5
268A	25.1	24.0	20.7				1840	0.254		17.5
269A	4.3	5.7	4.9				205	0.028		4.1
270A	10.3	12.3	10.6				890	0.123		9.6
271A	20.5	21.0	18.2				1680	0.232		15.4
272A	17.6	17.7	15.3				1500	0.207		13.0
273A	6.5	8.3	7.2	0.35			1175	0.162		6.5
274A	9.8	12.0	10.4				1515	0.209		12.3
275A	16.4	16.0	13.8				2130	0.294		16.3
277A	24.8	28.7	24.8				2330	0.322		29.3
278A	28.2	28.7	24.8				2540	0.351		29.4
279A	20.3	20.3	17.5				2245	0.310		20.7

\* G<sub>b</sub>, G', and G are each defined in Appendix A. Measurement G is the only term used to describe penetration resistance gradient in relations described in the body of this report.  
\*\* Load per wheel.

Table 12

Field Tests with Vehicles in Coarse-Grained Soils,  
Maximum Drawbar Pull, First Pass

Test No.*	Penetration Resistance		Wheel Load W, lb	Inflation Pressure, psi	Deflection Coef- ficient $\delta/h$	P/W†	Basic Prediction Term $\frac{G(b\delta)^{3/2}}{W} \cdot \frac{\delta}{h}$	
	Gradient, ** psi/in. G'	G						
<u>M38A1, 4x4 (Jeep); Padre Island, Tex.</u>								
2	125.7	108.7	672	30	0.086	0.243	42.7	
5	121.7	105.2	↓	20	0.113	0.320	53.2	
8	123.3	106.6		15	0.134	0.355	63.1	
11	104.7	90.5		10	0.173	0.416	70.0	
15	119.0	102.9	740	30	0.100	0.219	41.7	
18	127.3	110.1	↓	20	0.120	0.295	53.4	
21	117.3	101.4		15	0.156	0.361	64.0	
24	111.7	96.6		10	0.200	0.445	78.5	
29	96.7	83.6	800	30	0.100	0.223	31.5	
33	95.0	82.1	↓	20	0.130	0.242	40.0	
37	110.0	95.1		15	0.160	0.348	57.1	
42	113.7	98.3		10	0.210	0.387	77.6	
<u>M37, 4x4 Truck, 3/4-Ton; Padre Island, Tex.</u>								
44	122.3	105.7	1422	30	0.114	0.181	46.8	
47	115.7	100.0	↓	20	0.144	0.255	56.2	
50	103.3	89.3		15	0.168	0.297	58.3	
53	95.7	82.7		10	0.198	0.369	64.6	
58	104.0	89.9	1602	30	0.120	0.172	37.3	
62	112.3	97.1	↓	20	0.156	0.227	52.2	
66	110.0	95.1		15	0.192	0.283	63.1	
70	113.3	97.9		10	0.240	0.304	93.1	
73	90.7	78.4	1797	30	0.132	0.174	32.0	
74	120.0	103.7	↓	↓	0.199	0.199	42.2	
75	120.0	103.7			0.187	0.187	42.2	
79	28.7	24.8			0.125	0.125	10.2	
80	32.0	27.7	↓	↓	0.113	0.113	11.3	
82	112.3	97.1			20	0.180	0.253	53.7
86	20.7	17.9			↓	0.143	0.143	10.0
87	40.7	35.2	↓	↓	0.179	0.179	19.6	
89	100.0	86.4			15	0.216	0.291	57.5
93	23.0	19.9			↓	0.171	0.171	13.2
94	36.7	31.7	↓	↓	0.240	0.240	21.2	
97	110.0	95.1			10	0.276	0.361	80.8
101	32.7	28.3			↓	0.269	0.269	24.3
102	33.7	29.1	↓	↓	0.285	0.285	25.0	

(Continued)

\* "Test No." is "Item No." in reference 16.

\*\* G' and G are each defined in Appendix A. Measurement G is the only term used to describe penetration resistance gradient in relations described in the body of this report.

†  $P/W = \frac{\text{total pull}}{\text{total load}}$  or  $\frac{\text{pull per wheel}}{\text{load per wheel}}$ . s indicates that pull (P') was measured when the vehicle was operating upslope or downslope, where the slope angle ( $\theta$ ) varied between  $2.9^\circ$  and  $8.5^\circ$ . ss indicates that pull (P'') was measured when the vehicle was operating on a side slope, where the slope angle varied between  $3.4^\circ$  and  $6.3^\circ$ . The absence of s or ss indicates that the pull (P') was measured when the vehicle was operating upslope or downslope where the slope angle varied between  $-2^\circ$  and  $1.7^\circ$ . Values of P for all tests were obtained by correcting pull measured on a slope to pull (P) on a level surface by the equation

$$P = \frac{(P' + W \sin \theta)}{\cos \theta} \text{ for upslopes or downslopes, and by the equation } P = \frac{\sqrt{(P'')^2 + (W \sin \theta)^2}}{\cos \theta}$$

for side slopes. (These equations are developed and explained in reference 16.)

Table 12 (Continued)

Test No.	Penetration Resistance		Wheel Load W, lb	Inflation Pressure, psi	Deflection Coef- ficient $\delta/h$	P/W	Basic
	Gradient, psi/in. G'	G					Prediction Term $\frac{G(b\delta)^{3/2}}{W}$
<u>M37, 4x4 Truck, 3/4-Ton; Cape Cod, Mass.</u>							
103	42.7	36.9	1422	30	0.114	0.161	14.9
104	42.7	36.9		30	0.114	0.157	14.9
105	34.7	30.0		20	0.144	0.177	15.3
106	45.3	39.2		↓	↓	0.212	19.6
107	46.3	40.0				0.200	20.0
108	46.0	39.8		15	0.168	0.250	23.4
109	43.7	37.8		↓	↓	0.239	22.4
110	43.7	37.8				0.250	22.4
111	40.0	34.6		10	0.198	0.306	24.0
112	41.7	36.0		↓	↓	0.288	25.2
113	34.3	29.7				0.299	20.4
<u>M135, 6x6 Truck, 2-1/2-Ton; Padre Island, Tex.</u>							
147	108.3	93.6	2908	30	0.126	0.284	40.4
148	35.0	30.3		30	0.126	0.133	13.2
150	117.3	101.4		20	0.195	0.342	67.8
153	117.3	101.4		15	0.220	0.372	76.4
156	105.7	91.4		10	0.270	0.419	85.1
<u>M135, 6x6 Truck, 2-1/2-Ton; Vicksburg Miss., Miss. River Sandbar</u>							
159	48.0	41.5	3125	60	0.090	0.072	12.1
160	38.0	32.9		60	0.090	0.061	9.6
163	47.6	41.2		30	0.160	0.180	21.6
164	53.3	46.1		↓	↓	0.200	23.8
165	52.0	45.0				0.192	23.4
166	43.0	37.2		↓	↓	0.147	19.3
167	46.3	40.0				0.220	27.1
168	50.7	43.8		20	0.210	0.228	30.1
169	41.7	36.0		↓	↓	0.207	24.7
170	47.3	40.9				0.216	27.7
171	45.0	38.9		15	0.265	0.255	33.5
172	51.7	44.7		↓	↓	0.275	38.6
173	43.3	37.4				0.261	32.0
174	44.7	38.6		↓	↓	0.252	33.4
175	46.7	40.4				0.265	34.9
176	44.7	38.6		10	0.360	0.317	41.6
177	44.0	38.0		10	0.360	0.318	40.7
<u>M34, 6x6 Truck, 2-1/2-Ton; Suscinio, France</u>							
178	26.0	22.5	1962	20	0.132	0.159ss	15.1
179	30.7	26.5		20	0.132	0.154ss	18.0
180	17.0	14.7		15	0.147	0.157ss	11.1
181	23.3	20.1		↓	↓	0.151ss	14.8
182	30.7	26.5				0.144ss	20.1
183	31.3	27.1		10	0.176	0.22css	24.2
184	21.3	18.4		↓	↓	0.219ss	16.3
185	18.3	15.8				0.197ss	14.0

Table 12 (Continued)

Test No.	Penetration Resistance		Wheel Load W, lb	Inflation Pressure, psi	Deflection Coef- ficient $\delta/h$	P/W	Basic Prediction Term $G(bd)^{3/2} \cdot \frac{\delta}{h}$
	Gradient, psi/in. G'	G					
<u>M34, 6x6 Truck, 2-1/2-Ton; La Turballe, France</u>							
186	22.0	19.0	2796	10	0.250	0.255s	16.9
187	41.7	36.0	2796	10	0.250	0.283s	32.4
<u>DUKW 353, 6x6 Truck, 2-1/2-Ton; La Turballe, France</u>							
188	34.3	29.7	2445	15	0.203	0.249s	23.2
189	47.6	40.6	↓	15	0.203	0.293s	32.0
190	28.7	24.8	↓	10	0.252	0.316s	24.5
203	26.7	23.1	3278	20	0.225	0.212s	15.2
204	47.7	41.2	↓	20	0.225	0.195s	27.0
209	31.7	27.4	↓	15	0.277	0.289s	22.2
210	32.0	27.7	↓	↓	↓	0.261s	22.2
211	28.7	24.8	↓	↓	↓	0.262s	20.0
212	26.0	22.5	↓	10	0.348	0.305s	18.0
213	39.0	33.7	↓	↓	↓	0.328s	27.0
214	28.7	24.8	↓	↓	↓	0.322s	20.0
<u>DUKW 353, 6x6 Truck, 2-1/2-Ton; Suseinno, France</u>							
191	47.7	41.2	3278	30	0.171	0.215ss	20.6
192	44.3	38.3	↓	↓	↓	0.159ss	18.8
193	35.0	30.3	↓	↓	↓	0.190ss	15.0
194	35.3	30.5	↓	↓	↓	0.194ss	15.0
195	44.3	38.3	↓	↓	↓	0.194ss	18.8
196	46.7	40.4	↓	↓	↓	0.202ss	20.1
197	35.7	30.9	↓	20	0.225	0.263ss	20.3
198	22.3	19.3	↓	↓	↓	0.193ss	12.4
199	31.7	27.4	↓	↓	↓	0.216ss	10.1
200	22.3	19.3	↓	↓	↓	0.238ss	12.4
201	30.7	25.5	↓	↓	↓	0.188ss	17.9
202	34.7	30.0	↓	↓	↓	0.191ss	19.7
205	22.7	19.6	↓	15	0.277	0.193ss	13.6
206	20.3	17.5	↓	↓	↓	0.200ss	13.8
207	22.7	19.6	↓	↓	↓	0.230ss	15.9
208	23.0	19.9	↓	↓	↓	0.234ss	15.9
<u>DUKW 353, 6x6 Truck, 2-1/2-Ton; Cape Cod, Mass.</u>							
221	61.7	53.3	2548	20	0.176	0.244	34.8
222	53.0	45.8	↓	↓	↓	0.227	30.0
223	57.3	49.5	↓	↓	↓	0.262	32.2
224	16.7	14.4	↓	↓	↓	0.079	9.6
225	16.3	14.1	↓	↓	↓	0.093	9.5
226	20.0	17.3	↓	↓	↓	0.090	11.6
227	57.3	49.5	↓	15	0.216	0.317	38.9
228	60.7	52.5	↓	↓	↓	0.277	42.2
229	47.3	40.9	↓	↓	↓	0.293	32.9
230	15.3	13.2	↓	↓	↓	0.118	10.4
231	14.3	12.4	↓	↓	↓	0.105	9.8
232	13.3	11.5	↓	↓	↓	0.108	9.2
233	54.0	46.7	↓	10	0.262	0.370	45.7
234	53.3	46.1	↓	↓	↓	0.337	45.1
235	43.0	37.2	↓	↓	↓	0.340	36.3
236	13.3	11.5	↓	↓	↓	0.214	11.6
237	13.0	11.2	↓	↓	↓	0.213	11.2
238	14.7	12.7	↓	↓	↓	0.191	12.7

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(Continued)

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Table 12 (Continued)

Test No.	Penetration Resistance		Wheel Load W, lb	Inflation Pressure, psi	Deflection Coeff- ficient $\delta/h$	P/W	Basic Prediction Term $G(b\delta)^{3/2} \cdot \frac{\delta}{h}$	
	Gradient, psi/in. G'	G					W	h
<u>M41, 6x6 Truck, 5-Ton; Padre Island, Tex.</u>								
240	32.3	27.9	3845	30	0.172	0.169	24.6	
241	25.3	21.9		↓	↓	0.165	19.3	
243	113.3	97.9		↓	↓	0.327	86.4	
248	101.7	87.9		20	0.183	0.397	83.4	
251	33.0	28.5		15	0.258	0.283	38.1	
253	120.0	103.7		15	0.258	0.441	139.1	
258	120.0	103.7		10	0.316	0.479	170.2	
<u>Bucket Loader, 4x4 Tractor; Vicksburg, Miss., Miss. River Sandbar</u>								
285	40.7	35.2	2266	30	0.104	0.201	22.3	
286	42.7	36.9		↓	↓	0.203	23.4	
287	42.0	36.3		↓	↓	0.202	23.0	
288	37.3	32.2		↓	↓	0.192	20.5	
289	41.7	36.0		20	0.141	0.252	31.1	
290	40.0	34.6		20	0.141	0.238	29.7	
291	41.3	35.7		15	0.173	0.300	37.0	
292	40.3	34.8	↓	↓	↓	0.303	36.2	
293	39.0	33.7		↓	↓	0.289	35.4	
294	36.3	31.4		10	0.233	0.340	44.1	
295	41.0	35.4		10	0.233	0.355	50.3	
<u>Tournadozer, 4x4 Tractor; Vicksburg, Miss., Miss. River Sandbar</u>								
296	34.3	29.7	7768	30	0.178	0.216	36.6	
297	43.3	37.4		↓	↓	0.213	46.1	
298	38.3	33.1		↓	↓	0.215	41.1	
299	49.0	42.4		↓	↓	0.235	52.5	
300	47.0	40.6		↓	↓	0.216	50.1	
301	45.3	39.2		20	0.208	0.283	57.1	
302	46.0	39.8		↓	↓	0.272	57.7	
303	45.3	39.2	↓	↓	↓	0.302	57.1	
304	45.3	39.2		↓	↓	0.281	57.1	
305	40.7	35.2		↓	↓	0.287	50.5	
306	45.3	39.2		↓	↓	0.281	57.1	
307	46.0	39.8		↓	↓	0.272	57.7	
308	41.7	36.0		15	0.250	0.325	63.7	
309	41.3	35.7		↓	↓	0.327	63.1	
310	46.3	40.0	↓	↓	↓	0.339	70.4	
311	45.0	38.9		↓	↓	0.327	68.6	
312	43.3	37.4		↓	↓	0.316	65.6	
313	41.3	35.7		↓	↓	0.338	63.1	
314	44.7	38.6		↓	↓	0.332	74.3	
315	44.3	38.3		↓	↓	0.338	73.5	
316	38.7	33.5		10	0.272	0.397	64.5	
317	45.7	39.5	↓	↓	↓	0.402	75.6	
318	38.7	33.5		↓	↓	0.389	64.5	
319	46.0	39.8		↓	↓	0.412	76.6	
320	44.3	38.3		↓	↓	0.399	75.6	
<u>GOER, 4x4 Cargo Carrier, 5-Ton (18-26); Vicksburg, Miss., Miss. River Sandbar</u>								
321	47.7	41.2	6668	30	0.17	0.278	42.2	
322	37.7	32.6		↓	↓	0.254	33.6	
323	39.7	34.3		↓	↓	0.241	35.1	
324	44.0	38.0		↓	↓	0.274	39.0	
325	46.7	40.4		↓	↓	0.261	41.4	
326	47.7	41.2		↓	↓	0.267	42.2	
327	42.0	36.3		↓	↓	0.268	37.5	
328	50.3	43.5	↓	20	0.215	0.335	55.4	

(Continued)

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Table 12 (Concluded)

Test No.	Penetration Resistance		Wheel Load W, lb	Inflation Pressure, psi	Deflection	P/W	Basic	
	Gradient, psi/in. G'	G			Coef- ficient $\delta/h$		Prediction Term $\frac{G(b\delta)^{3/2}}{W}$	
GOER, 4x4 Cargo Carrier, 5-Ton (18-26); Vicksburg, Miss., Miss. River Sandbar (Continued)								
329	50.3	43.5	6668	20	0.215	0.345	56.4	
330	45.3	39.2				0.305	51.1	
331	42.0	36.3				0.320	46.8	
332	44.6	38.6				0.327	50.1	
333	45.0	38.9				0.325	50.6	
334	52.3	45.2			15	0.247	0.380	66.7
335	48.7	42.1					0.388	62.2
336	45.3	39.2					0.400	57.9
337	47.3	40.9					0.374	60.3
338	49.0	42.4					0.366	62.2
339	48.0	41.5					0.366	61.0
340	42.0	36.3			10	0.294	0.431	64.1
341	48.3	41.8					0.447	74.2
342	47.0	40.6					0.444	71.9
343	49.7	43.0					0.428s	75.6

GOER, 4x4 Cargo Carrier, 5-Ton (15-34); Vicksburg, Miss., Miss. River Sandbar							
344	45.0	38.9	6668	30	0.217	0.240	52.0
345	44.0	38.0				0.250	51.0
346	44.7	38.6				0.241s	51.5
347	48.0	41.4				0.248	55.0
348	47.3	40.9				0.235	54.1
349	48.0	41.5				0.259	55.2
350	43.3	37.4		20	0.242	0.313	54.7
351	45.3	39.2				0.309	57.0
352	43.3	37.4				0.311	54.7
353	41.0	35.4				0.308	51.9
354	43.3	37.4				0.306	54.7
355	43.3	37.4		15	0.296	0.300	54.7
356	43.0	37.2				0.303	54.2
357	48.3	41.8				0.356	75.4
358	47.6	41.2				0.356	74.7
359	44.7	38.6				0.354	70.1
360	49.3	42.6		10	0.428	0.359	77.6
361	47.0	40.6				0.350	73.9
362	47.0	40.6				0.352	73.9
363	45.3	39.2				0.349	71.0
364	46.3	40.0				0.348	72.3
365	50.3	43.5				0.427	114.5
366	48.3	41.7				0.425	109.9
367	46.3	40.0				0.409	104.8
368	45.0	37.2				0.411	97.3
369	42.0	36.3				0.390s	96.7

Table 13

Field Tests with Vehicles in Coarse-Grained Soils,  
Towed, First Pass

Test No.*	Penetration Resistance: Gradient**		Wheel Load W , lb	Inflation Pressure psi	Deflection Coef- ficient $\delta/h$	$P_T/W^\dagger$	Basic Prediction	
	psi/in.						$G(b\delta)^{3/2}$ W	$\cdot \frac{\delta}{h}$
	G'	G						
<u>M37, 4x4 Truck, 3/4-Ton; Padre Island, Tex.</u>								
1	110.0	95.1	1797	30	0.132	0.020	38.3	
2	119.7	103.5	↓	20	0.180	0.001	57.7	
3	124.0	107.2		15	0.216	0.023	71.4	
4	103.0	89.0		10	0.275	0.065	24.5	
5	47.0	40.6		30	0.132	0.125	16.6	
6	56.7	49.0		20	0.180	0.076	27.3	
7	58.0	50.1		15	0.216	0.043	33.3	
8	54.7	47.3		10	0.275	0.051	40.4	
<u>M135, 6x6 Truck, 2-1/2-Ton; Padre Island, Tex.</u>								
9	27.3	23.6	2458	30	0.120	0.164	11.4	
10	42.7	36.9	↓	20	0.166	0.036	25.1	
11	36.3	31.4		15	0.185	0.131	22.9	
12	26.0	22.5		10	0.250	0.061	22.8	
13	41.3	35.7	2908	30	0.130	0.142	15.4	
14	10.7	9.3	↓	20	0.200	0.161	6.2	
15	11.0	9.5		15	0.260	0.138	8.2	
16	10.3	8.9		10	0.360	0.148	12.0	
<u>M135, 6x6 Truck, 2-1/2-Ton; Vicksburg, Miss., Miss. River Sandbar</u>								
17	40.3	34.8	3053	30	0.130	0.090	14.9	
18	42.3	36.6	3053	10	0.360	0.091	50.3	
<u>M135, Tested as 4x4; Vicksburg, Miss., Miss. River Sandbar</u> <u>(11.00-20, 12-PR Tires, Std NDCC Tread)</u>								
19	42.3	36.6	4402	30	0.232	0.093	19.1	
20	33.3	28.8	↓	20	0.235	0.091	19.1	
21	37.3	32.2		15	0.348	0.082	25.2	

(Continued)

\* "Test No." is "Item No." in reference 16.

\*\*  $G'$  and  $G$  are each defined in Appendix A. Measurement  $G$  is the only term used to describe penetration resistance gradient in relations described in the body of this report. $\dagger P_T/W = \frac{\text{total towed force}}{\text{total vehicle weight}} = \frac{\text{towed force per wheel}}{\text{wheel load}}$ Towed force ( $P_T'$ ) was measured on slopes where the slope angle ( $\theta$ ) varied between  $1.4^\circ$  and  $-1.2^\circ$ . Corresponding values of  $P_T$  on a level surface were obtained by correcting the measured  $P_T'$  values by the equation
$$P_T = \frac{P_T' - W \sin \theta}{\cos \theta} \quad \text{(This equation is developed and explained in reference 16.)}$$

Table 13 (Concluded)

Test No.	Penetration Resistance Gradient		Wheel Load W, lb	Inflation Pressure psi	Deflection Coef- ficient $\delta/h$	$P_T/W$	Basic Prediction Term	
	psi/in.						$G(b\delta)^{3/2}$	
	G'	G					W	h
<u>M135, Tested as 4x4; Vicksburg, Miss., Miss. River Sandbar</u> <u>(11.00-20, 2-PR Tires, Tread Removed)</u>								
22	28.3	24.5	4402	30	0.226	0.073	12.5	
23	34.3	29.7	↓	20	0.295	0.068	19.7	
24	34.0	29.4	↓	15	0.348	0.059	23.2	
<u>DUKW 353, 6x6 Truck, 2-1/2-Ton; Cape Cod, Mass.</u>								
25	45.7	39.5	2548	30	0.125	0.132	18.5	
26	37.3	32.2	↓	20	0.176	0.096	20.9	
27	38.0	32.9	↓	15	0.216	0.083	26.4	
28	29.3	25.3	↓	10	0.262	0.147	24.4	
<u>M41, 6x6 Truck, 2-1/2-Ton; Padre Island, Tex.</u>								
29	13.7	11.8	3845	30	0.144	0.203	7.2	
30	8.3	7.2	↓	20	0.194	0.160	7.2	
31	7.7	6.7	↓	15	0.234	0.119	8.1	
32	10.0	8.6	↓	10	0.316	0.125	14.1	
33	23.3	20.1	4695	30	0.172	0.145	14.2	
34	62.0	53.6	↓	20	0.210	0.060	47.1	
35	100.7	87.1	↓	15	0.300	0.025	109.7	
36	55.3	47.8	↓	10	0.375	0.044	69.0	
<u>Bucket Loader, 4x4 Tractor; Vicksburg, Miss., Miss. River Sandbar</u>								
48	45.0	38.9	3399	30	0.104	0.059	24.5	
49	39.0	33.7	↓	20	0.141	0.061	21.3	
50	39.0	33.7	↓	15	0.173	0.060	26.2	
51	37.0	32.0	↓	10	0.283	0.078	45.1	
<u>Tournadozer, 4x4 Tractor; Vicksburg, Miss., Miss. River Sandbar</u>								
52	42.7	36.9	7768	30	0.178	0.085	46.1	
53	43.3	37.4	↓	20	0.208	0.069	53.9	
54	44.7	38.6	↓	15	0.250	0.072	67.9	
55	42.0	36.3	↓	10	0.272	0.055	69.0	
<u>GOER, 4x4 Cargo Carrier, 5-Ton (18-26); Vicksburg, Miss., Miss. River Sandbar</u>								
56	42.0	36.3	6668	30	0.172	0.065	37.3	
57	45.0	38.9	↓	20	0.215	0.056	49.9	
58	48.0	41.5	↓	15	0.247	0.052	61.1	
<u>GOER, 4x4 Cargo Carrier, 5-Ton (15-34); Vicksburg, Miss., Miss. River Sandbar</u>								
60	48.0	41.5	6668	30	0.217	0.056	54.8	
61	43.0	37.2	↓	20	0.242	0.059	54.8	
62	46.3	40.0	↓	15	0.296	0.055	71.5	

Table 14

Field Tests with Vehicles in Fine-Grained Soils, Optimum Slip Point, First Pass

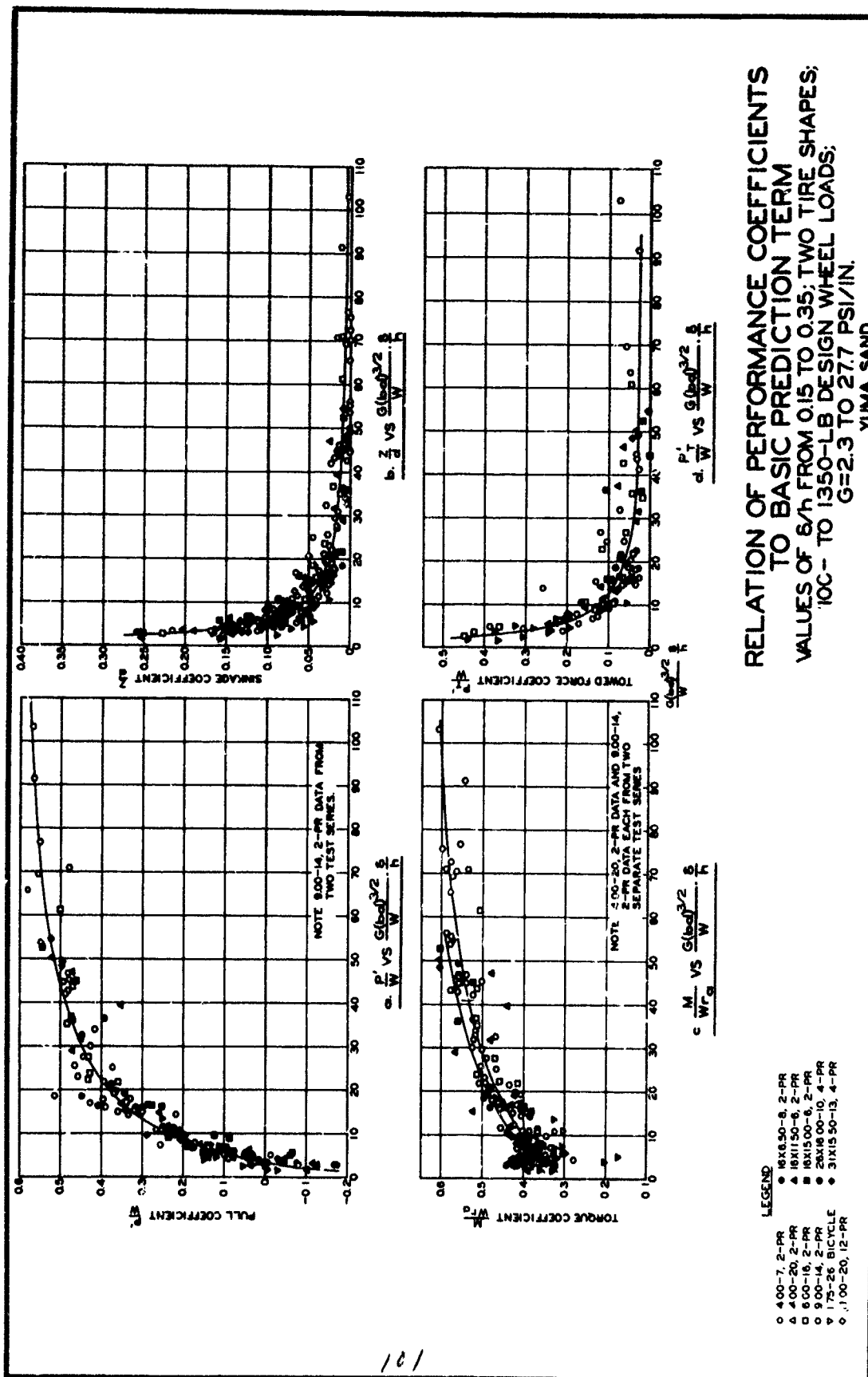
Test No.	Soil Type	Rating Cone Index 0- to 6-in. Layer	Nominal Tire Characteristics					Pull Coefficient* P/W	$\frac{C_{qd} \cdot (\frac{h}{n})^{1/2}}{1 + \frac{b}{2d}}$		$\frac{(WET)_{qd}}{M} \cdot (\frac{h}{n})^{1/2}$	Soil Data							
			Overall Diameter d, in.	Width b, in.	Inflation Pressure psi	Deflection Coefficient N/n	Load W, lb		Optimum Slip S, %	Per Wheel		Total	Scale Index C, at Depth, in.	Average Cone Index C, at	0- to 6-in. Layer	Rating Cone Index			
1-12	CL	1-12	18,030	38.2	7.3	0.20	20	1-03	18,030	0.68	17.4	15.1	64	69	64	69	8.85	32	
							20			0.66	13.3	10.1	51	51	48	46	0.78	35	
							21			0.70	13.3	10.1	51	51	48	46	0.78	35	
							19			0.70	17.1	12.1	56	56	64	64	0.66	32	
							20			0.48	9.6	6.7	73	73	33	33	0.69	23	
							19			0.47	9.6	6.7	37	37	35	35	0.69	23	
							18			0.67	29.3	47.0	158	158	78	78	1.60	162	
							18			0.70	29.3	47.0	158	158	78	78	1.60	162	
							17			0.13	5.8	3.9	30	30	23	23	0.65	13	
							23			0.13	6.7	4.3	34	34	23	23	0.65	13	
							16			0.66	22.7	21.2	88	88	96	96	0.93	73	
							21			0.43	6.4	4.2	24	24	21	21	0.78	17	
13-17	CL	20							0.32	6.4	4.6	26	26	26	26	0.78	16		
		10							0.16	4.6	2.9	18	18	19	19	0.61	10		
		11							0.14	5.2	3.2	18	18	19	19	0.61	11		
		11							0.14	5.2	3.2	18	18	19	19	0.61	11		
		12							0.14	5.5	3.5	20	20	21	21	0.61	12		
MZA 10x10																			
23-29	CL	45.0	30.9	9.0	0.20	18	2377	17,013	0.65	15.0	11.2	66	71	66	71	0.74	33		
						15			0.38	7.4	5.3	38	37	35	35	0.71	25		
						16			0.36	8.4	5.1	48	44	40	40	0.71	25		
						16			0.34	8.4	5.1	48	44	40	40	0.71	25		
						20			0.65	14.6	6.1	64	64	69	69	0.73	29		
						24			0.72	14.6	10.3	82	71	65	65	0.71	49		
						30			0.16	4.4	2.7	19	18	20	21	0.61	13		
						23			0.15	4.4	2.7	22	22	20	21	0.61	13		
						20			0.15	4.9	3.0	22	22	20	21	0.61	13		
						23			0.15	4.9	3.0	26	27	28	23	0.62	13		
		MZA 10x1																	
		50-56	CL	16,504	39.1	11.4	0.25	18	2653	16,504	0.53	7.7	5.8	65	71	65	67	0.74	50
						16			0.32	7.7	5.8	65	71	65	67	0.74	50		
						16			0.45	5.5	3.8	59	55	48	48	0.74	37		
						20			0.36	5.5	4.3	61	59	55	48	0.77	37		
						25			0.20	3.9	2.8	39	35	34	34	0.71	24		
63-68	CL					19			0.20	3.9	2.8	39	35	35	34	0.71	24		
MZA 10x12																			
37-46	CL	42.2	11.0	26.1	0.25	24	3038	16,225	0.39	3.2	2.5	54	59	54	48	0.77	37		
						22			0.25	3.2	2.2	59	54	48	48	0.77	37		
						22			0.36	7.6	11.6	98	98	103	112	1.34	172		
Log Emitter, Model 8-112																			
74-91	CH	62.5	23.2	1.0	0.165	22	4124	16,495	0.69	8.9	8.9	78	78	74	74	1.00	74		
						22			0.31	5.4	4.7	59	59	45	45	0.87	39		
						20			0.60	11.4	11.0	110	110	95	95	0.96	91		
						25			0.58	7.7	6.3	69	69	64	64	0.84	54		
						30			0.60	7.2	5.1	74	74	69	69	0.71	49		
91-95	CH					20			0.65	7.8	7.8	78	78	74	74	1.00	91		
						20			0.65	7.8	7.8	78	78	74	74	1.00	91		
						15			0.60	10.0	9.5	108	108	95	95	0.96	91		
						15			0.60	10.0	9.5	108	108	95	95	0.96	91		
						16			0.54	6.3	5.2	71	71	60	60	0.84	50		

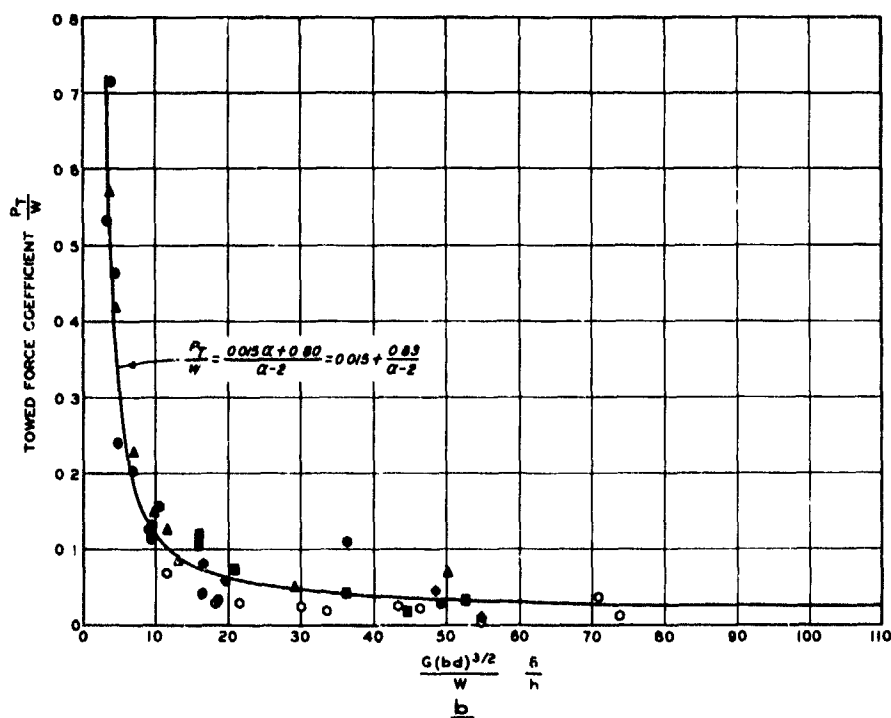
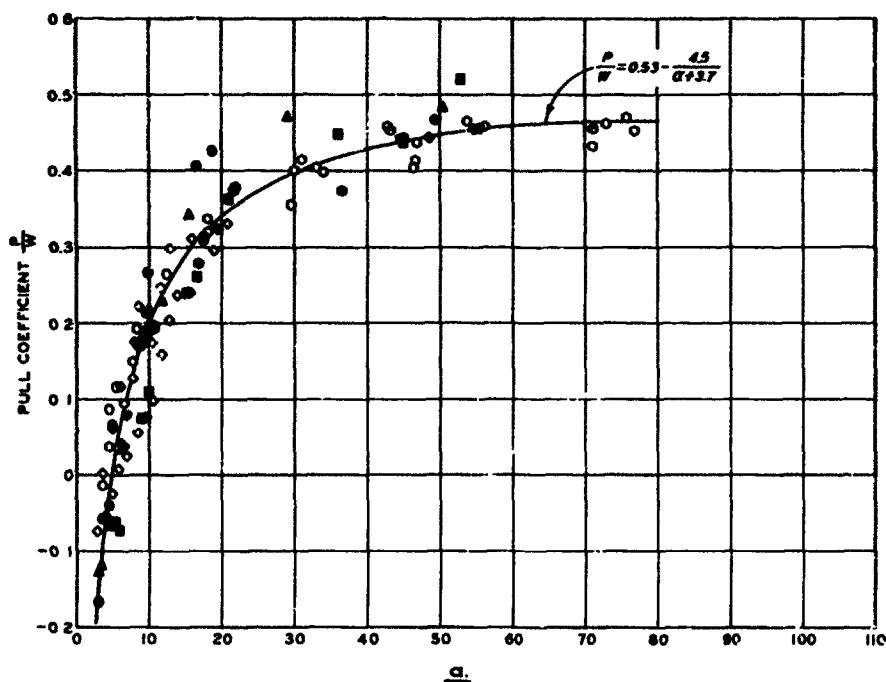
Table 15

Field Tests with Vehicles in Fine-Grained Soils, Towed, First Pass

Test No.	Soil Type	Rating Cone Index RCI	Nominal Tire Characteristics						Towed Force Coef- ficient* P <sub>T</sub> /W	Cbd W · (b/h) <sup>1/2</sup> · 1 1 + 2b	(RCI)bd W · (b/h) <sup>1/2</sup> · 1 1 + 2b	Soil Data						0- to 6-in. Layer Remold- ing Cone Index RI
			Overall Diam- eter d, in.	Width b, in.	Infla- tion Pres- sure psi	Deflec- tion Coef- ficient δ/h	Cone Index C at Depth, in.											
							0	1				2	3	4	5	6		
MEXA 10x10																		
27	CL	35	43.9	38.7	7.3	0.20		0.07	13.3	10.1	29	34	47	56	55	51	48	
30S	CL	52						0.04	17.4	15.1	33	45	59	73	78	69	64	
31	CL	23						0.08	9.6	6.7	22	32	36	37	36	35	32	
95	CH	162						0.04	29.3	47.0	100	114	128	130	86	72	78	
122S	CL	13						0.09	5.8	3.8	19	23	20	20	20	19	18	
1-4	CL	12						0.10	5.5	3.5	14	18	18	19	20	20	21	
MEXA 8x8																		
104	CL	25	48.0	30.9	9.0	0.20		0.09	7.4	5.3	31	30	33	39	40	38	37	
105	CL	29						0.08	8.1	6.1	22	28	39	46	52	48	44	
106S	CL	49						0.07	14.6	10.3	52	62	72	81	82	71	66	
154	CH	13						0.17	4.4	2.7	21	23	22	22	19	18	20	
157	CH	14						0.22	4.9	3.0	12	19	21	25	26	27	28	
X4410EX																		
56	CL	50	39.1	14.4	12.2	0.25		0.09	7.7	5.8	38	57	70	83	82	71	65	
59	CL	37						0.13	5.5	4.3	25	34	46	56	61	59	55	
62	CL	24						0.20	3.9	2.8	21	30	38	39	39	35	35	
68	CH	189						0.06	11.9	22.0	89	106	139	134	93	78	84	
M3542 (Modified)																		
46	CL	50	42.2	11.0	20.1	0.25		0.11	4.5	3.8	39	57	71	84	83	72	66	
49	CL	37						0.19	3.2	2.5	25	34	47	56	61	59	54	
68	CH	172						0.08	7.6	11.6	70	111	150	138	111	98	103	
Log S-112, Model S-112																		
10	CH	74	62.5	23.2	16.0	0.165		0.07	8.9	8.9	66	--	--	76	--	--	78	
12	CH	41						0.10	5.7	4.9	30	--	--	48	--	--	63	
14	CH	39						0.10	5.4	4.7	30	--	--	46	--	--	59	
1-1	CH	91						0.07	11.4	11.0	68	--	--	103	--	--	110	
18	CH	54						0.08	7.7	6.5	47	--	--	69	--	--	77	
4	CH	49	52.8			0.200		0.06	7.2	5.1	65	--	--	74	--	--	69	
6	CH	26						0.13	3.6	2.7	26	--	--	36	--	--	40	
9	CH	74						0.08	7.8	7.8	68	--	--	76	--	--	78	
11	CH	41						0.12	4.9	4.3	30	--	--	48	--	--	63	
13	CH	39						0.12	4.7	4.1	30	--	--	46	--	--	59	
15	CH	91						0.06	10.0	9.5	68	--	--	108	--	--	110	
17	CH	50						0.06	6.3	5.2	45	--	--	63	--	--	71	

\*  $P_t/W$  represents the ratio of total towed force to total load.





#### LEGEND

- 4 00-7, 2-PR
- 9 00-14, 2-PR
- 11 00-20, 12-PR
- 16 X 8 50-8, 2-PR
- ▲ 16 X 11 50-8, 2-PR
- 16 X 15 00-8, 2-PR
- 28 X 16 00-10, 4-PR
- ◆ 31 X 15 50-13, 4-PR

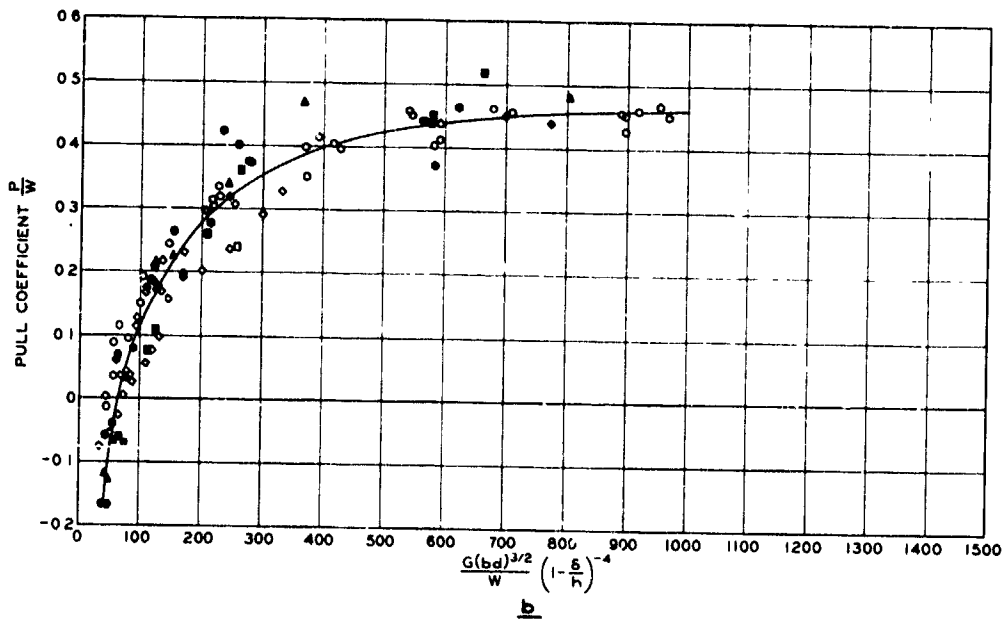
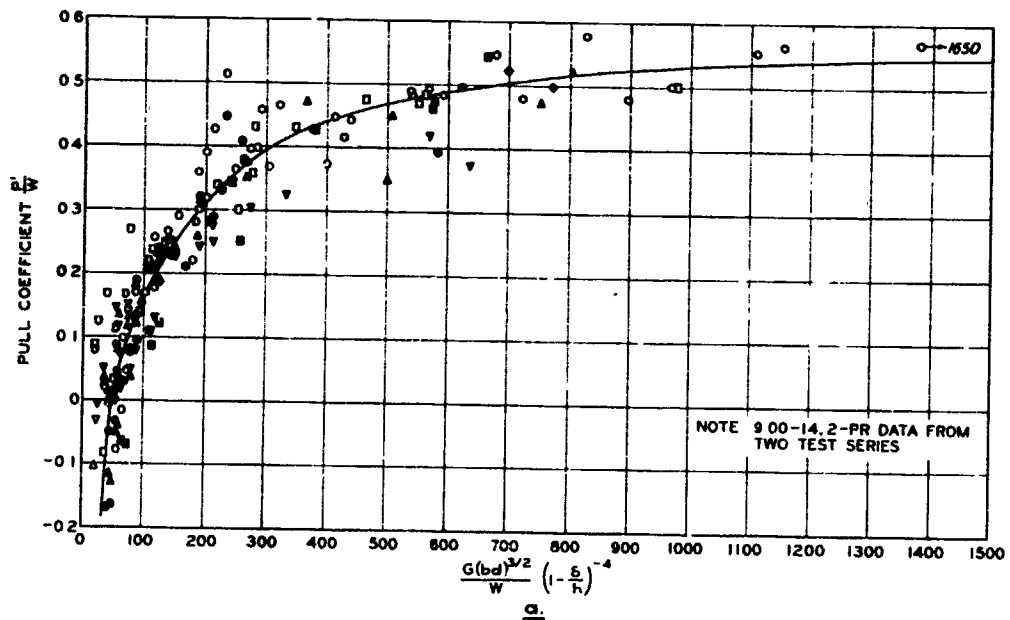
NOTE  $\alpha = \frac{G(bd)^{3/2}}{W} \cdot \frac{b}{h}$

#### RELATION OF PULL AND TOWED FORCE COEFFICIENTS TO BASIC PREDICTION TERM

VALUES OF  $b/h$  FROM 0.15 TO 0.35; TWO TIRE SHAPES; 4+ TO 4500-LB DESIGN WHEEL LOADS;  $G=3.2$  TO 19.9 PSI/IN.

YUMA SAND

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#### LEGEND

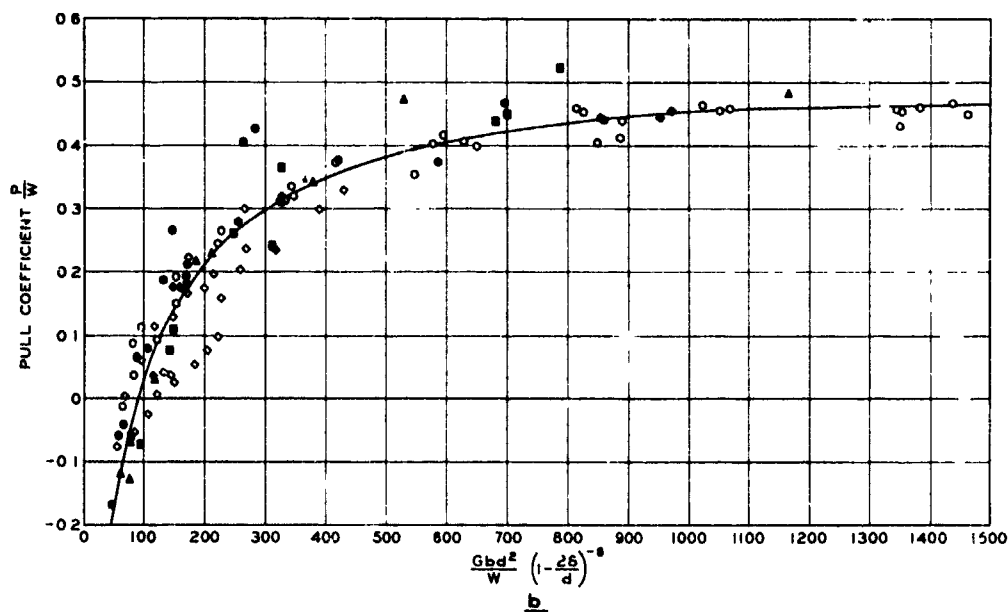
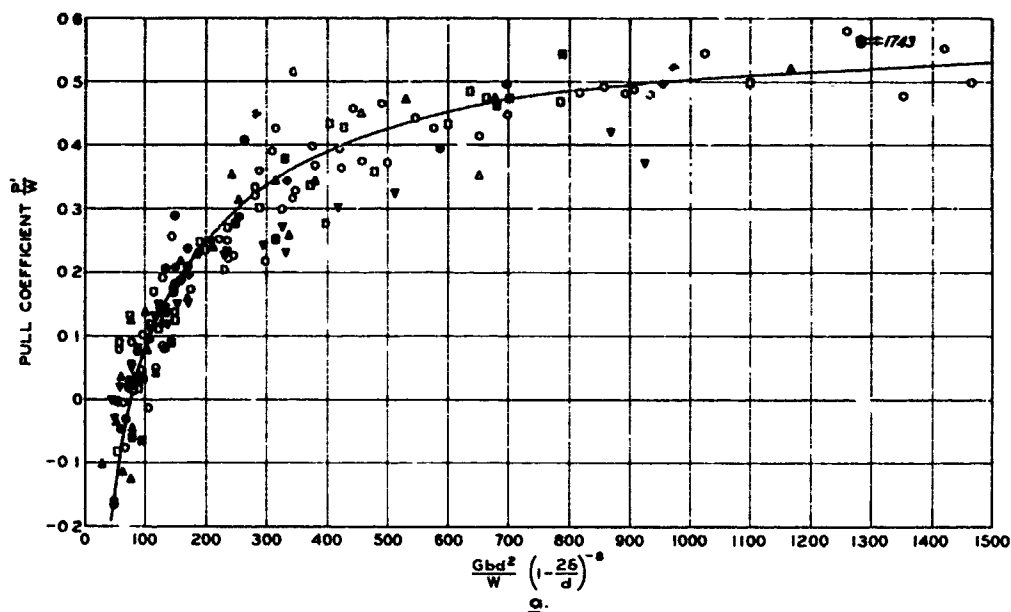
- 400-7, 2-PR
- △ 400-20, 2-PR
- 6 00-16, 2-PR
- 9 00-14, 2-PR
- ▽ 1 75-26, BICYCLE
- 1100-20, 12-PR
- 16 X 6 50-8, 2-PR
- △ 16 X 11 50-8, 2-PR
- 16 X 15 00-6, 2-PR
- 26 X 16 00-10, 4-PR
- 31 X 15 50-13, 4-PR
- ▽ 27 90 X 12 00, RIGID
- 27 80 X 6 00, RIGID
- 27 90 X 3 00, RIGID

#### RELATION OF $P'/W$ AND $P/W$ TO ALTERNATIVE PREDICTION TERM

$$G(bd)^{3/2}/W \cdot (1 - \delta/h)^{-4}$$

VALUES OF  $\delta/h$  FROM 0.15 TO 0.35;  
TWO TIRES SHAPES, THREE RIGID WHEELS;  
44- TO 4500-LB DESIGN WHEEL LOADS;  
G=2.3 TO 277 PSI/IN.

YUMA SAND



#### LEGEND

- 4 00-7, 2-PR
- △ 4 00-20, 2-PR
- 6 00-16, 2-PR
- ◇ 9 00-14, 2-PR
- ▽ 1 75-26, BICYCLE
- 11 00-20, 12-PR
- 16 X 6 50-8, 2-PR
- △ 16 X 11 50-6, 2-PR
- 16 X 15 00-6, 2-PR
- 26 X 16 00-10, 4-PR
- 31 X 15 50-13, 4-PR
- ▽ 27 90 X 12 00, RIGID
- ◇ 27 80 X 6 00, RIGID
- 27 90 X 3 00, RIGID

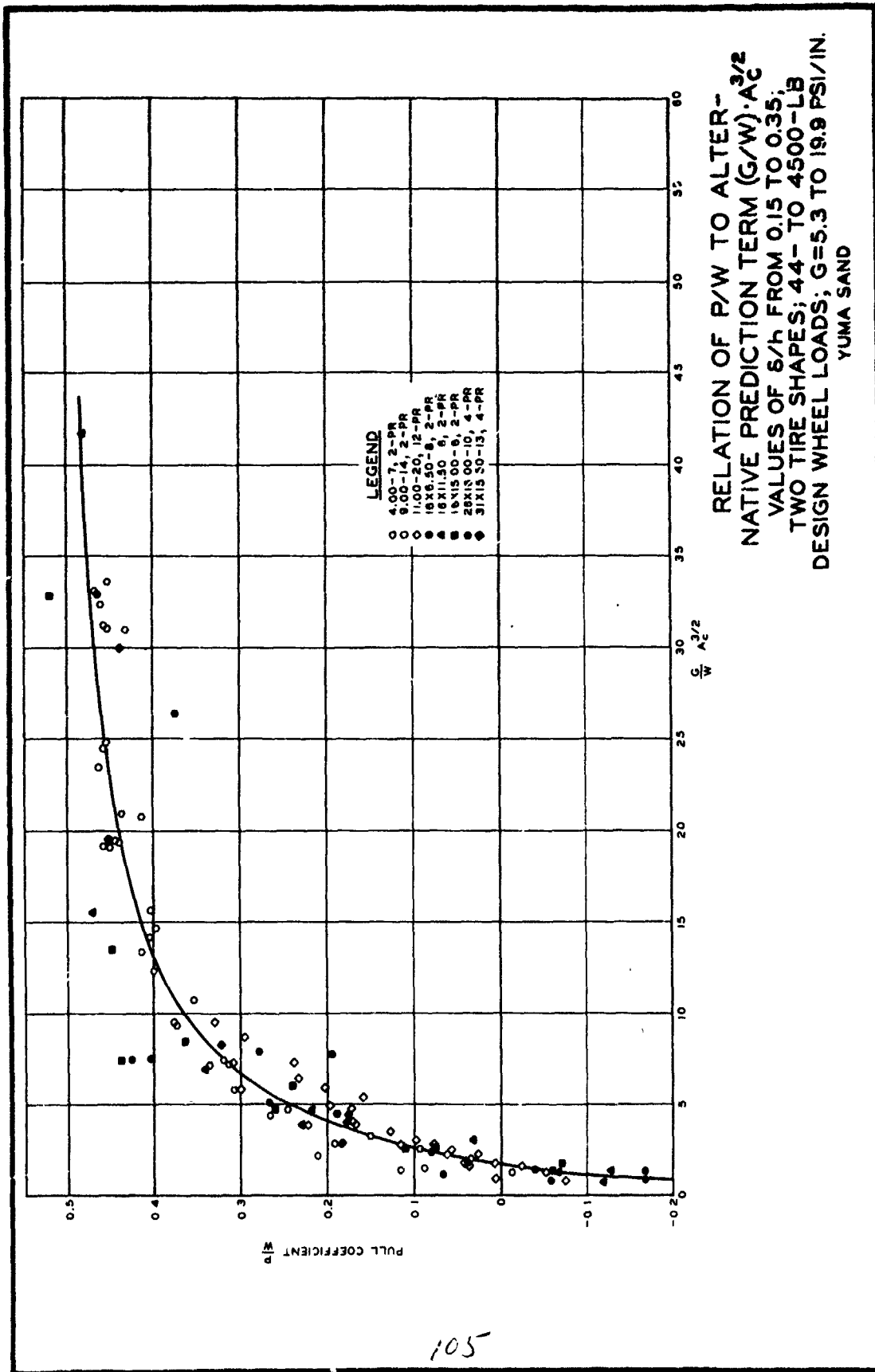
#### RELATION OF P'/W AND P/W TO ALTERNATIVE PREDICTION TERM

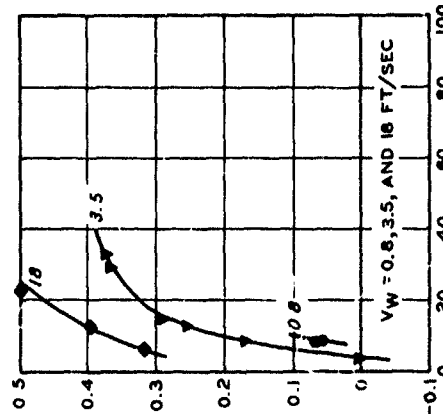
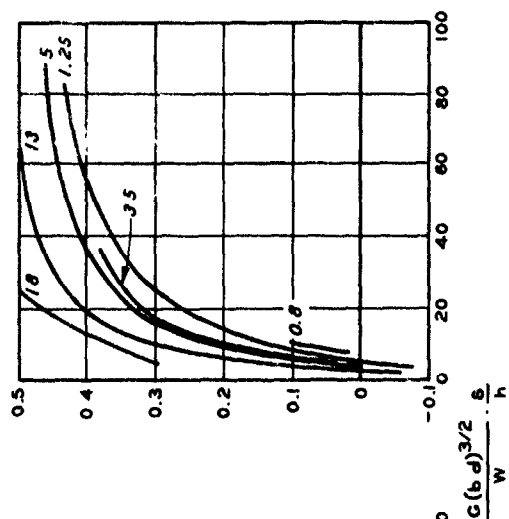
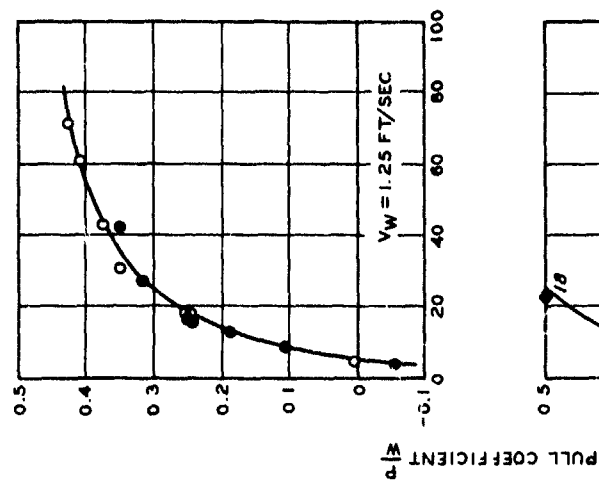
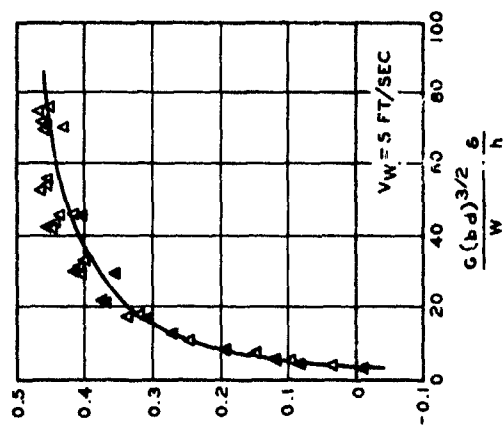
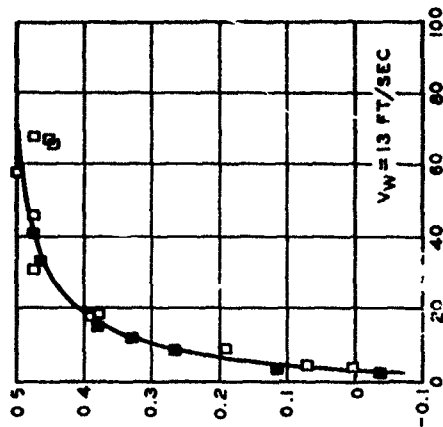
$$Gbd^2/W \cdot [1 - (2\delta/d)]^{-8}$$

VALUES OF  $\delta/h$  FROM 0.15 TO 0.35;  
TWO TIRES SHAPES; THREE RIGID WHEELS;  
44- TO 4500-LB DESIGN WHEEL LOADS;  
 $G=2.3$  TO 27.7 PSI/IN.

YUMA SAND

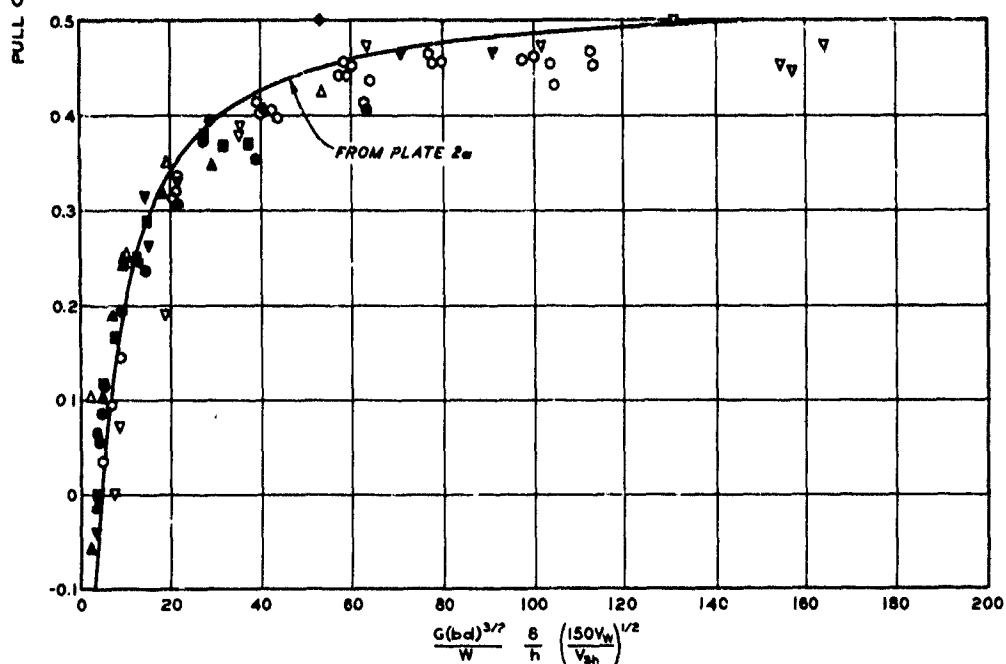
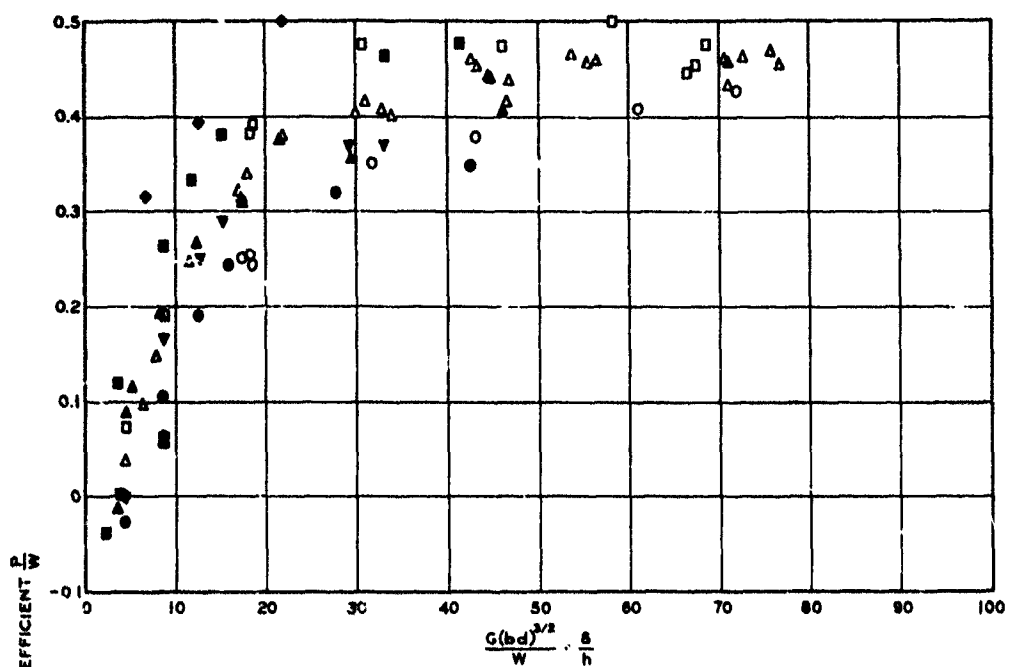
104





NOTE: OPEN SYMBOLS: 9.00-14, 2-PR TIRE.  
CLOSED SYMBOLS: 4.00-7, 2-PR TIRE.  
 $V_W$ : WHEEL TRANSLATIONAL VELOCITY.

**INFLUENCE OF WHEEL  
TRANSLATIONAL VELOCITY  
ON PULL COEFFICIENT**  
DESIGN DEFLECTION  $\delta/h = 0.25$ ;  
44- TO 1432-LB LOADS;  
 $G = 2.1 \text{ TO } 19.7 \text{ PSI/IN.}$   
20 PERCENT SLIP  
YUMA SAND

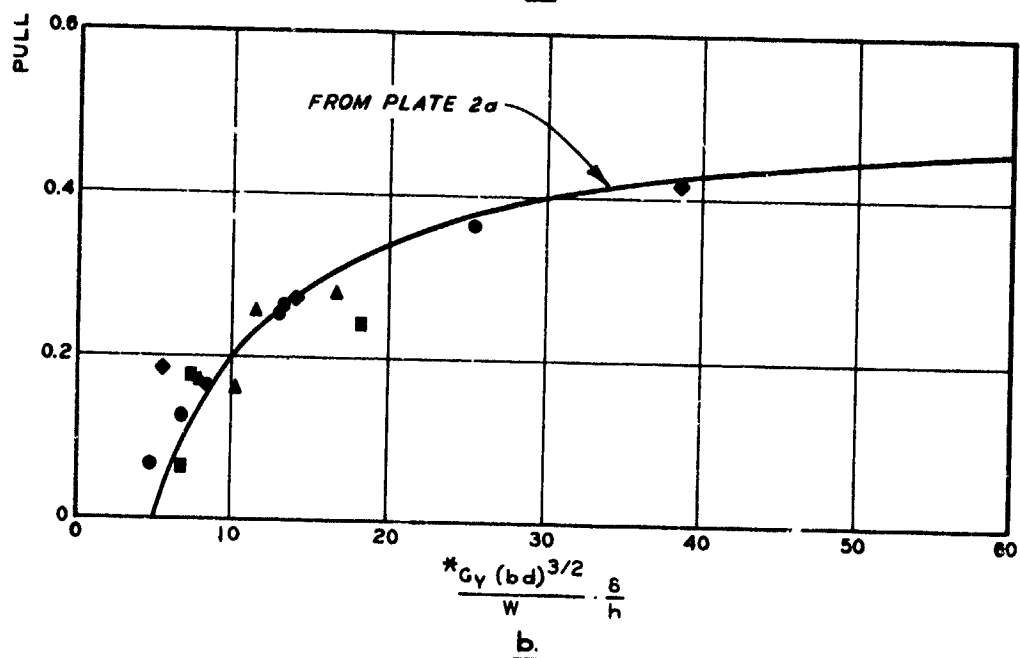
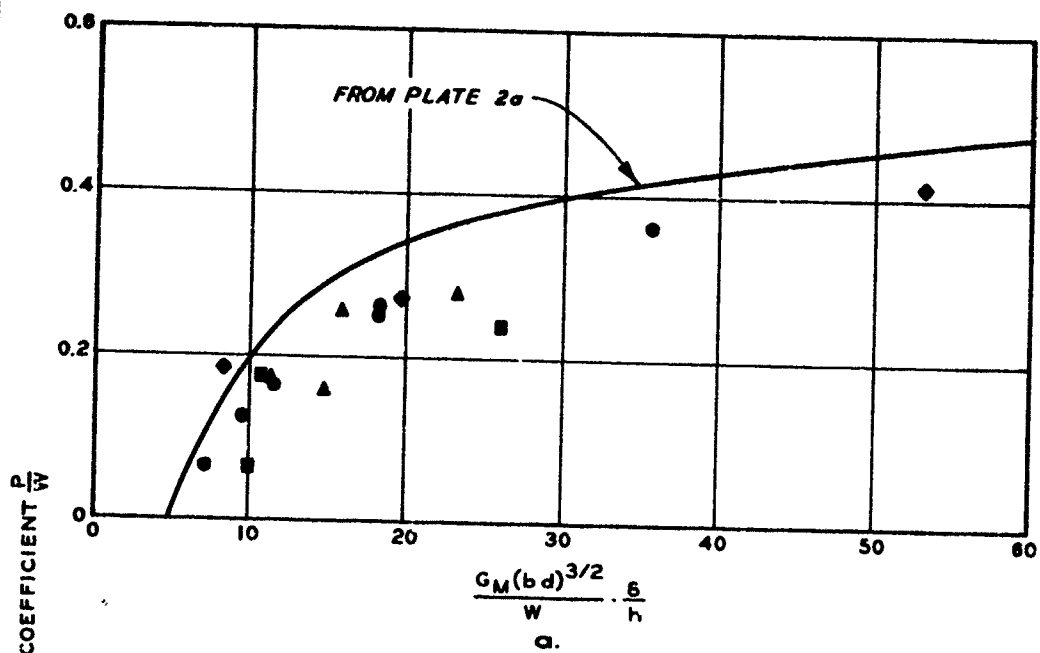


#### LEGEND

	$V_W$ , FT/SEC
○	0.8
△	1.25
□	3.5
○	5
▽	13
○	18

NOTE: OPEN SYMBOLS: 900-14, 2-PR TIRE  
CLOSED SYMBOLS: 4.00-7, 2-PR TIRE

USE OF  $(150V_W/V_{Sh})^{1/2}$  TO ACCOUNT  
FOR EFFECTS OF VELOCITY  
ON TIRE PERFORMANCE  
DESIGN DEFLECTION  $b/h=0.25$ ;  
44- TO 1432-LB LOADS;  
 $G=2.1$  TO 19.7 PSI/IN.  
20 PERCENT SLIP  
YUMA SAND



### LEGEND

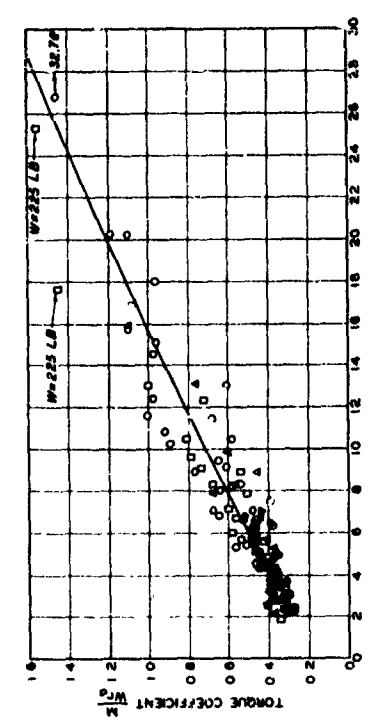
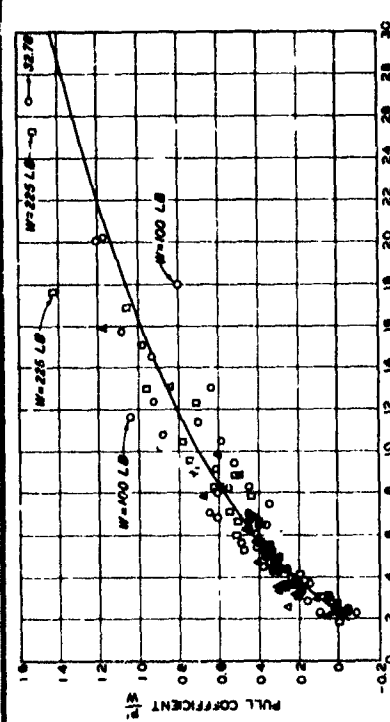
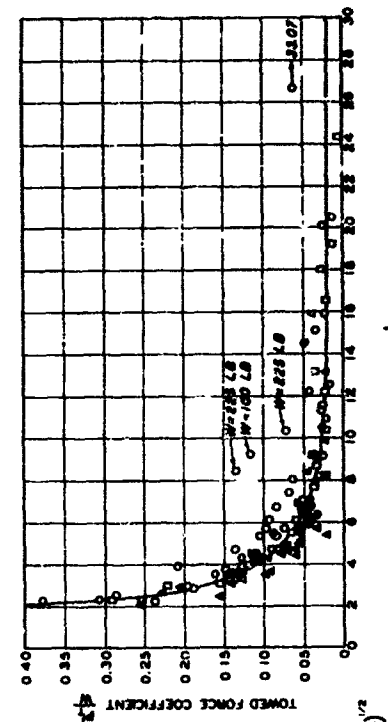
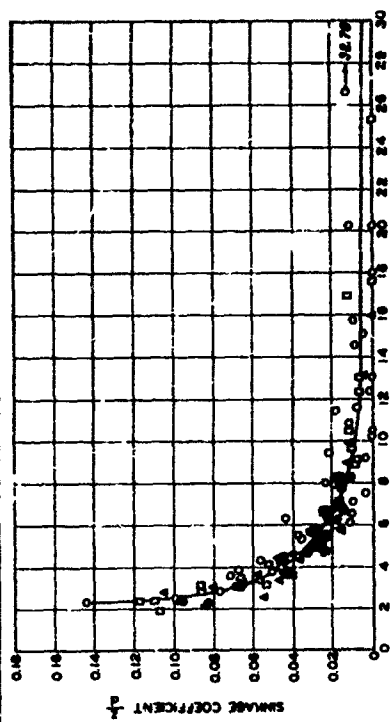
- 16X6.50-8, 2-PR
- ▲ 16X11.50-8, 2-PR
- 16X15.00-8, 2-PR
- 26X16.00-10, 4-PR
- ◆ 31X15.50-13, 4-PR

\* PENETRATION RESISTANCE GRADIENT  $G_M$  MEASURED IN MORTAR SAND WAS CONVERTED TO THE CORRESPONDING MEASUREMENT IN YUMA SAND  $G_Y$  BY THE METHOD DESCRIBED IN PARAGRAPH 32.

### RELATION OF PULL COEFFICIENT TO BASIC PREDICTION TERM

VALUES OF  $\delta/h$  FROM 0.15 TO 0.35  
225- TO 1350-LB  
DESIGN WHEEL LOADS;  
 $G=3.2$  TO 27.4 PSI/IN.

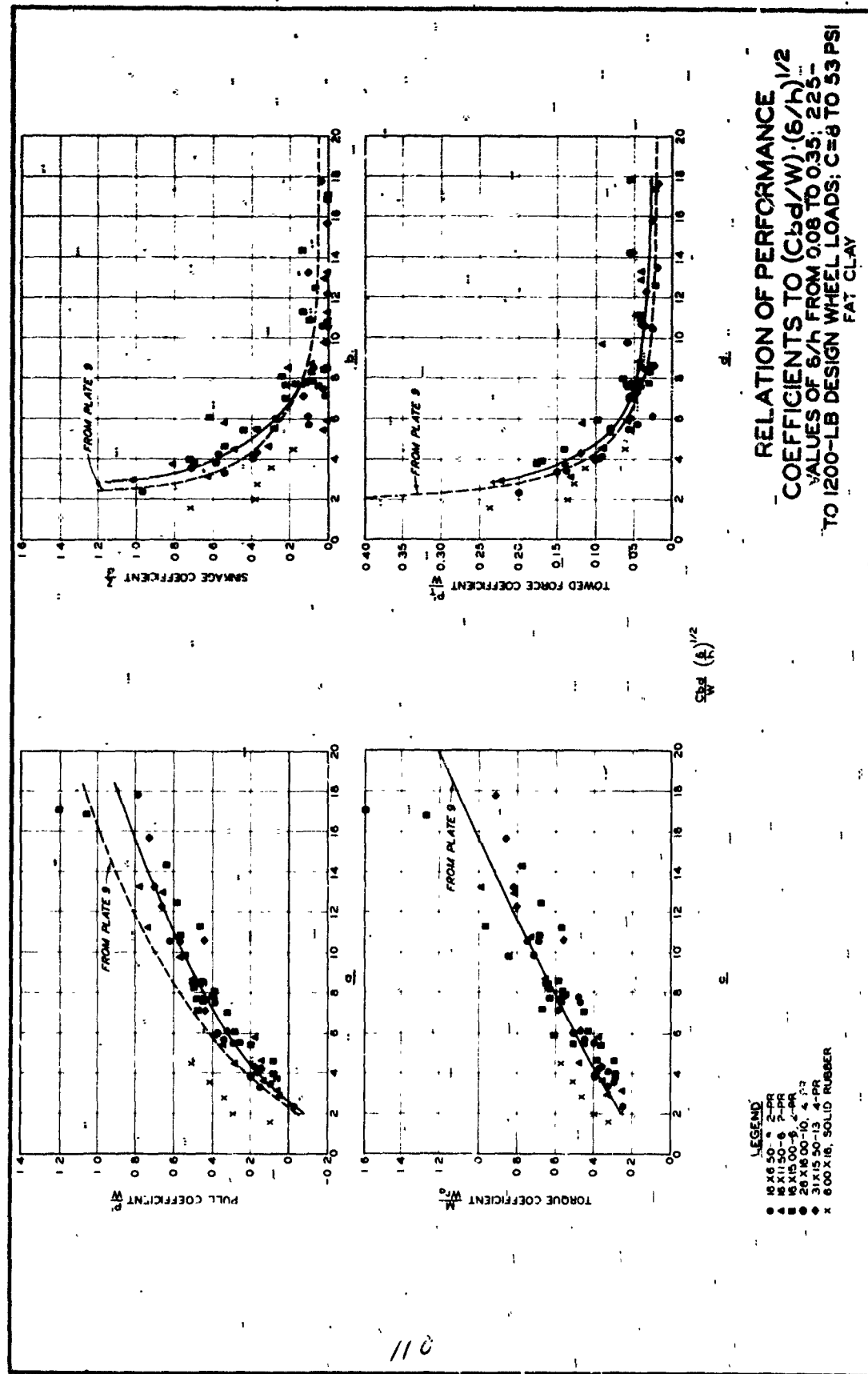
MORTAR SAND

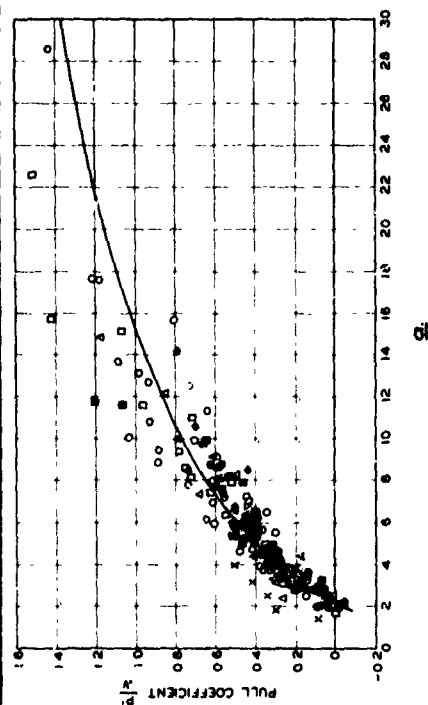


RELATION OF PERFORMANCE  
COEFFICIENTS TO  
( $C_{bd}/W$ ) ( $\delta/h$ )<sup>1/2</sup>  
VALUES OF  $\delta/h$  FROM 0.08 TO 0.45;  
100-- TO 4500-LB DESIGN  
WHEEL LOADS; C=16 TO 68 PSI  
FAT CLAY

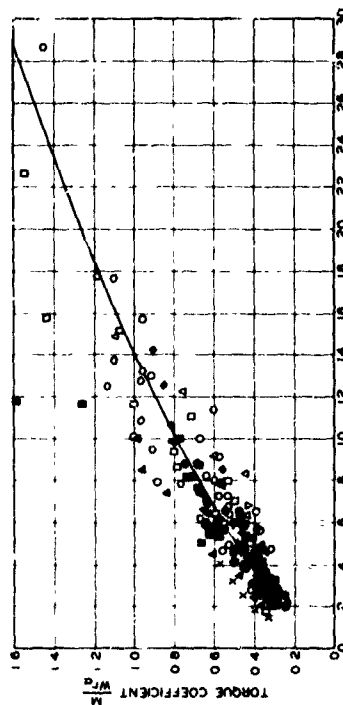
LEGEND  
O 4.00-7.2-PR  
Δ 4.00-20-2-PR  
□ 6.00-14-2-PR  
▽ 1.75-28-2-PR

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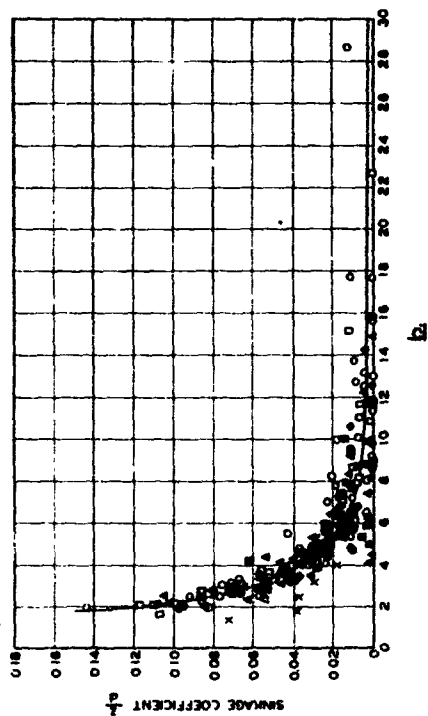




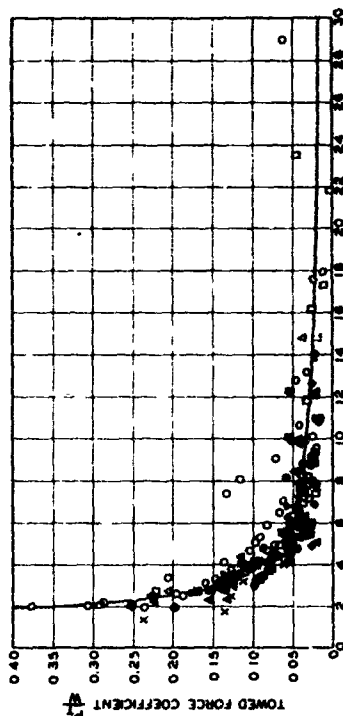
a.



b.



c.

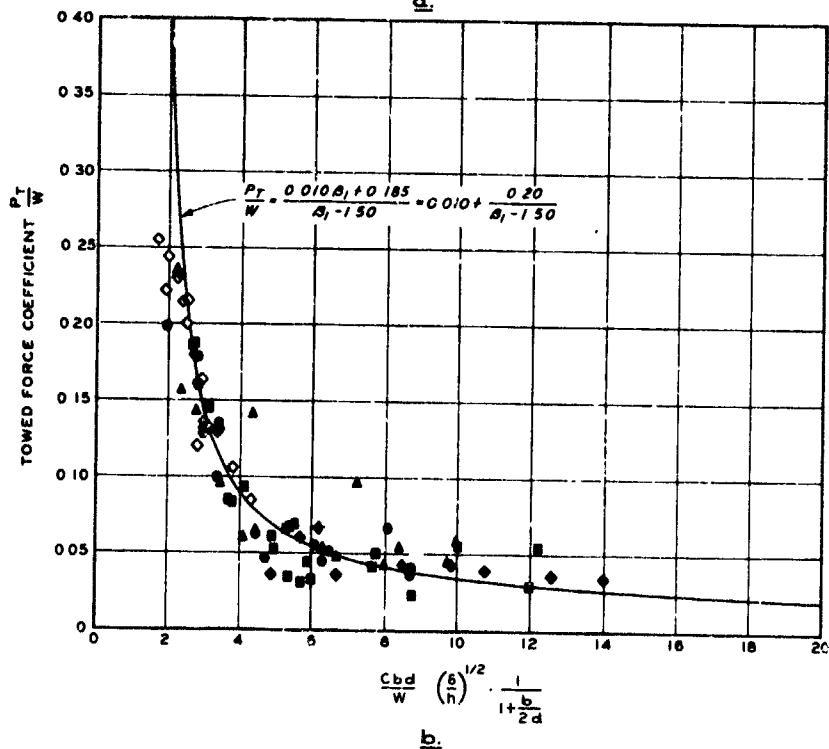
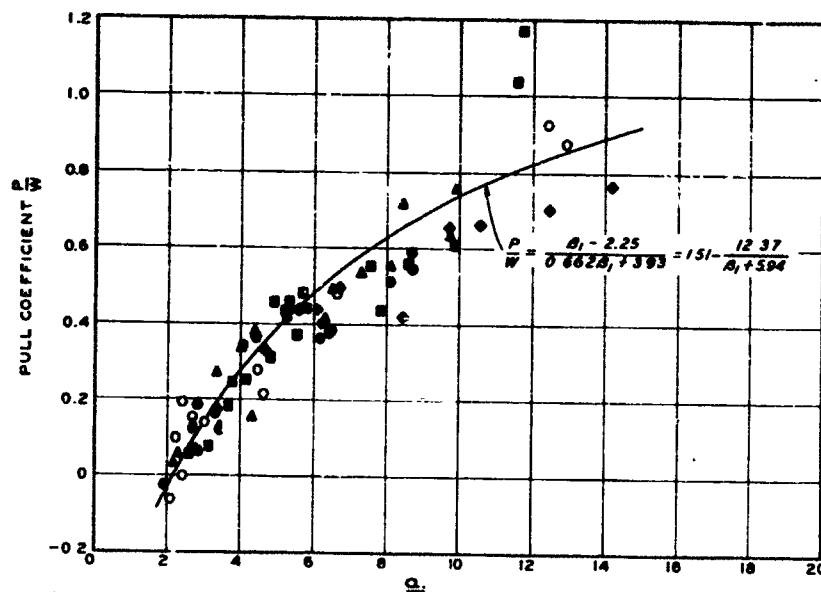


d.

$$\frac{Cbd}{W} \left( \frac{S}{h} \right)^{1/2} \frac{1}{1 + \frac{S}{2d}}$$

RELATION OF PERFORMANCE  
COEFFICIENTS TO  
 $(Cbd/W) \cdot (S/h)^{1/2} \cdot [1/(1+(S/2d))]$   
VALUES OF S/h FROM 0.01 TO 0.45;  
TWO TIRE SHAPES;  
100- TO 4500-LB DESIGN  
WHEEL LOADS; C=8 TO 68 PSI  
FAT CLAY

LEGEND:  
O 4.00-7.2-PR 8 18 X 50-8 2-PR  
Δ 4.00-20 2-PR A 18 X 50-8 2-PR  
□ 6.00-16 2-PR B 18 X 50-8 2-PR  
○ 9.00-14 2-PR C 28 X 50-10 4-PR  
X 75-26 INCH CYCLE 31 X 50-13 4-PR  
X 6.00-16, SOLID RUBBER



#### LEGEND

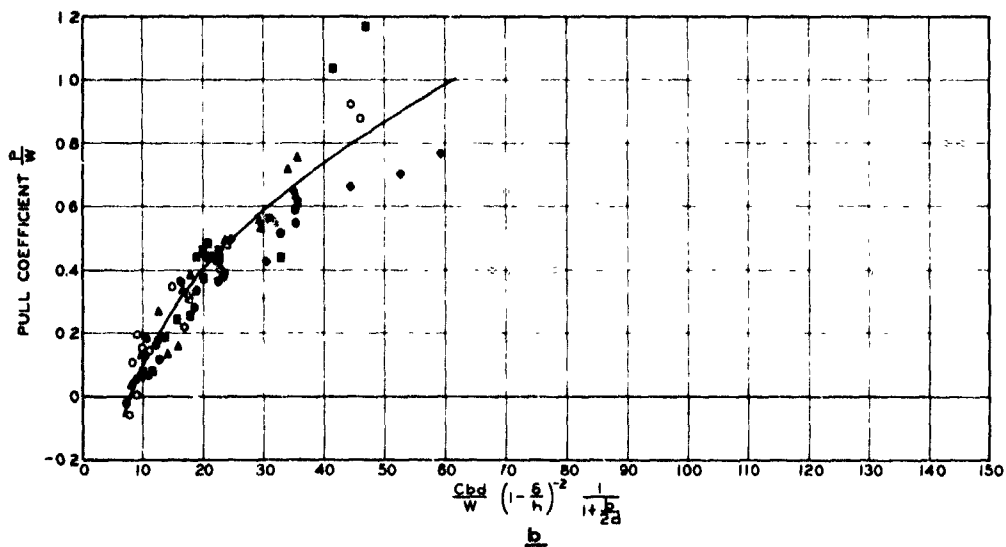
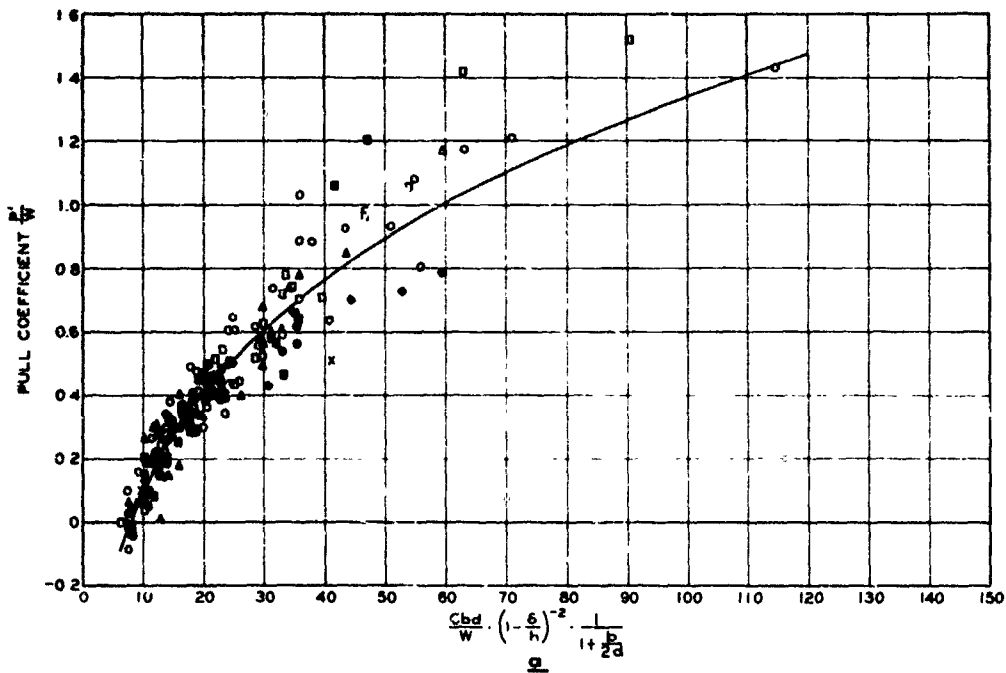
- 400-7, 2-PR
- 900-14, 2-PR
- 1100-20, 12-PR
- 16X8 50-8, 2-PR
- ▲ 16X11 50-6, 2-PR
- 16X15 00-6, 2-PR
- ▲ 26X16 00-10, 4-PR
- ◆ 31X15 50-13, 4-PR

NOTE  $A_1 = \frac{Cbd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + \frac{b}{2d}}$

#### RELATION OF PULL AND TOWED FORCE COEFFICIENTS TO BASIC PREDICTION TERM

VALUES OF  $\delta/h$  FROM 0.08 TO 0.35; TWO TIRE SHAPES; 50- TO 4500-LB DESIGN WHEEL LOADS; C = 8 TO 57 PSI

FAT CLAY



#### LEGEND

- o 4 00-7, 2-PR
- Δ 4 00-20, 2-PR
- 6 00-16, 2-PR
- 9 00-14, 2-PR
- ▽ 1 75-26, BICYCLE
- 16 X 6 50-8, 2-PR
- ▲ 16 X 11 50-8, 2-PR
- 16 X 15 00-6, 2-PR
- 28 X 18 00-10, 4-PR
- ◆ 31 X 15 50-13, 4-PR
- x 6 00-16, SOLID RUBBER

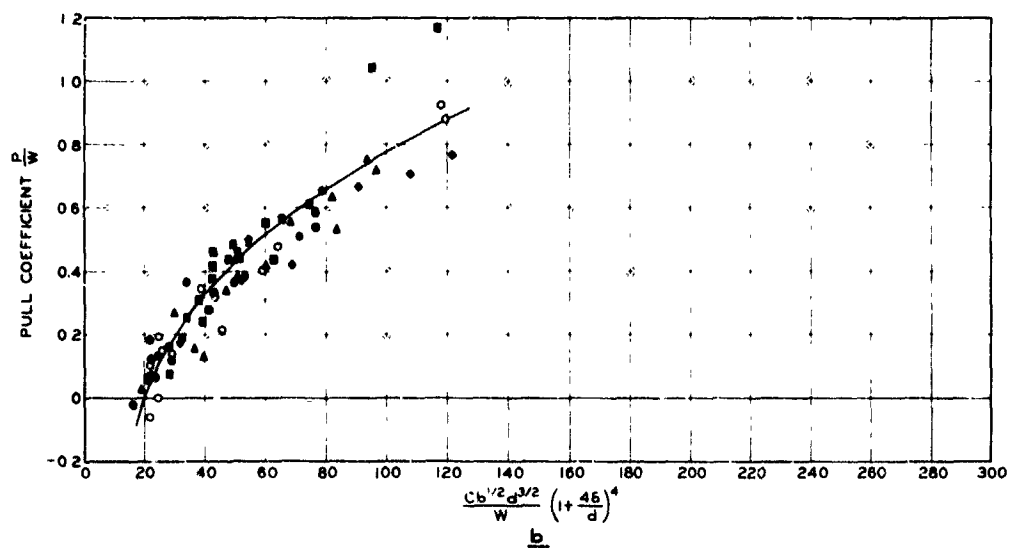
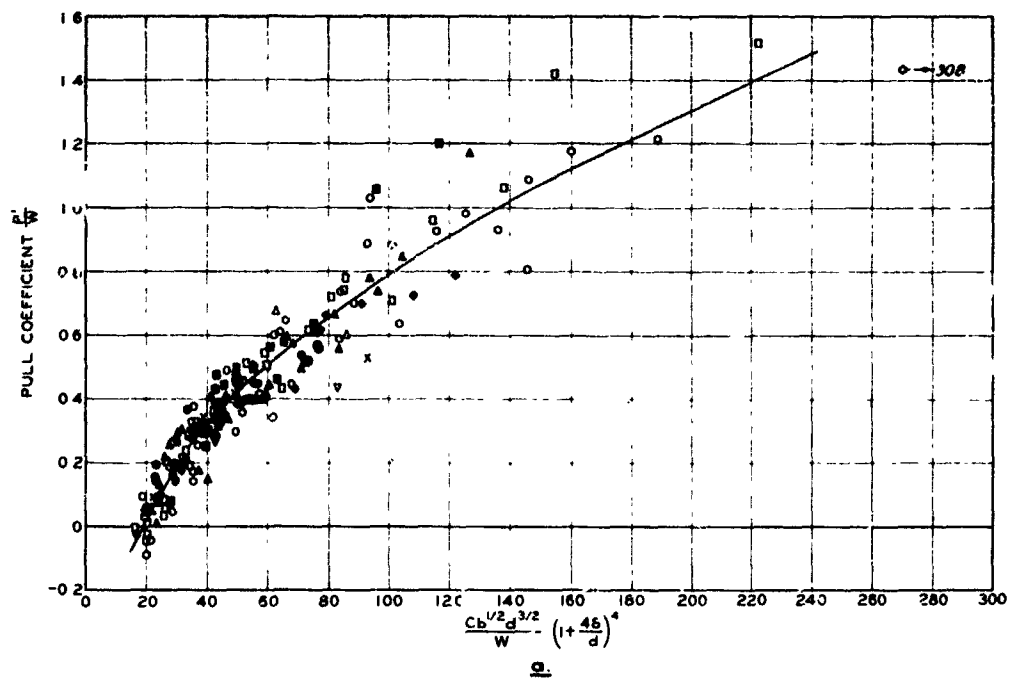
#### RELATION OF PULL COEFFICIENT TO ALTERNATIVE PREDICTION TERM

$$Cb d / W \cdot (1 - 6/h)^{-2} \cdot 1 / (1 + b/2d)$$

VALUES OF  $6/h$  FROM 0.01 TO 0.45;  
TWO TIRE SHAPES; 50- TO 1840-LB  
DESIGN WHEEL LOADS;

C=8 TO 68 PSI  
FAT CLAY

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#### LEGEND

- o 4 00-7, 2-PR
- Δ 4 00-20, 2-PR
- 6 00-16, 2-PR
- 9 00-14, 2-PR
- ▽ 1 73-26, BICYCLE
- 16 X 6 50-8, 2-PR
- ▲ 16 X 11 50-6, 2-PR
- 16 X 15 00-6, 2-PR
- △ 26 X 16 00-10, 4-PR
- 31 X 15 50-13, 4-PR
- × 6 00-16, SOLID RUBBER

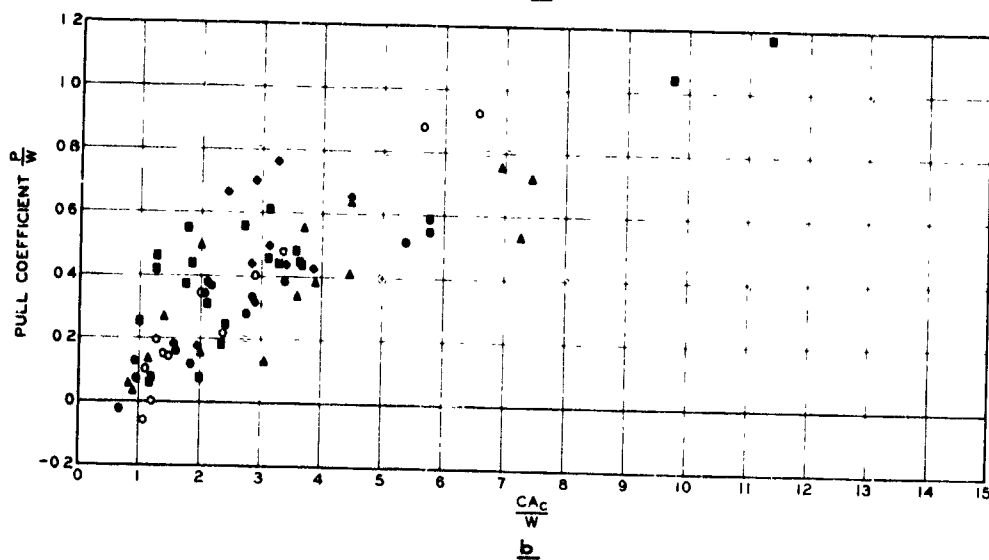
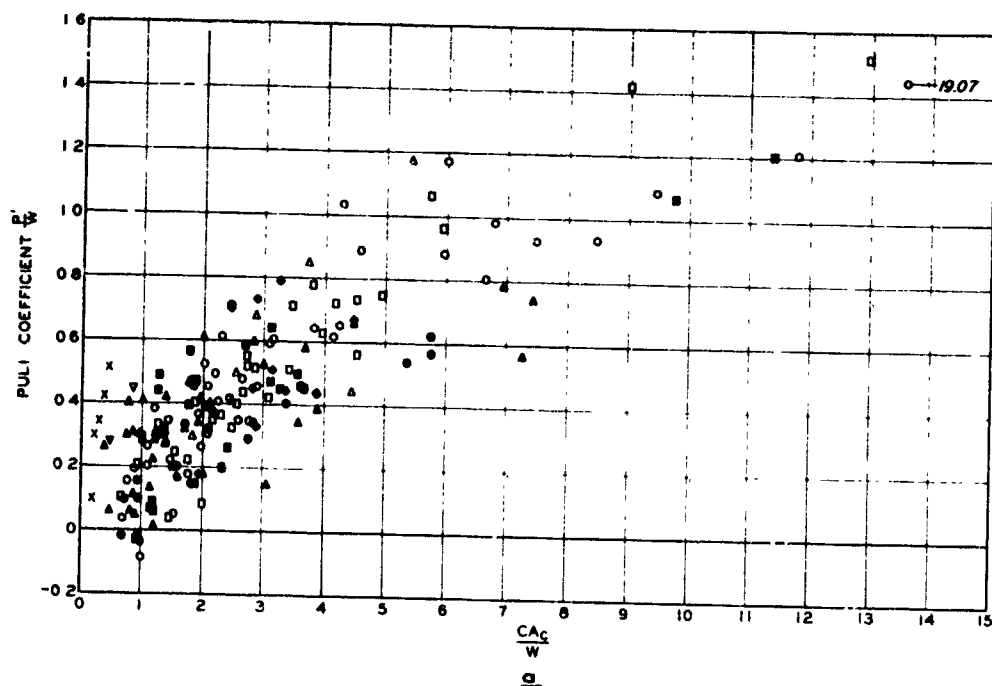
#### RELATION OF PULL COEFFICIENT TO ALTERNATIVE PREDICTION TERM

$$Cb^{1/2}d^{3/2}/W \cdot \left[1 + \frac{46}{d}\right]^4$$

VALUES OF  $b/h$  FROM 0.01 TO 0.45;  
TWO TIRE SHAPES; 50- TO 1840-LB  
DESIGN WHEEL LOADS;

C=8 TO 68 PSI  
FAT CLAY

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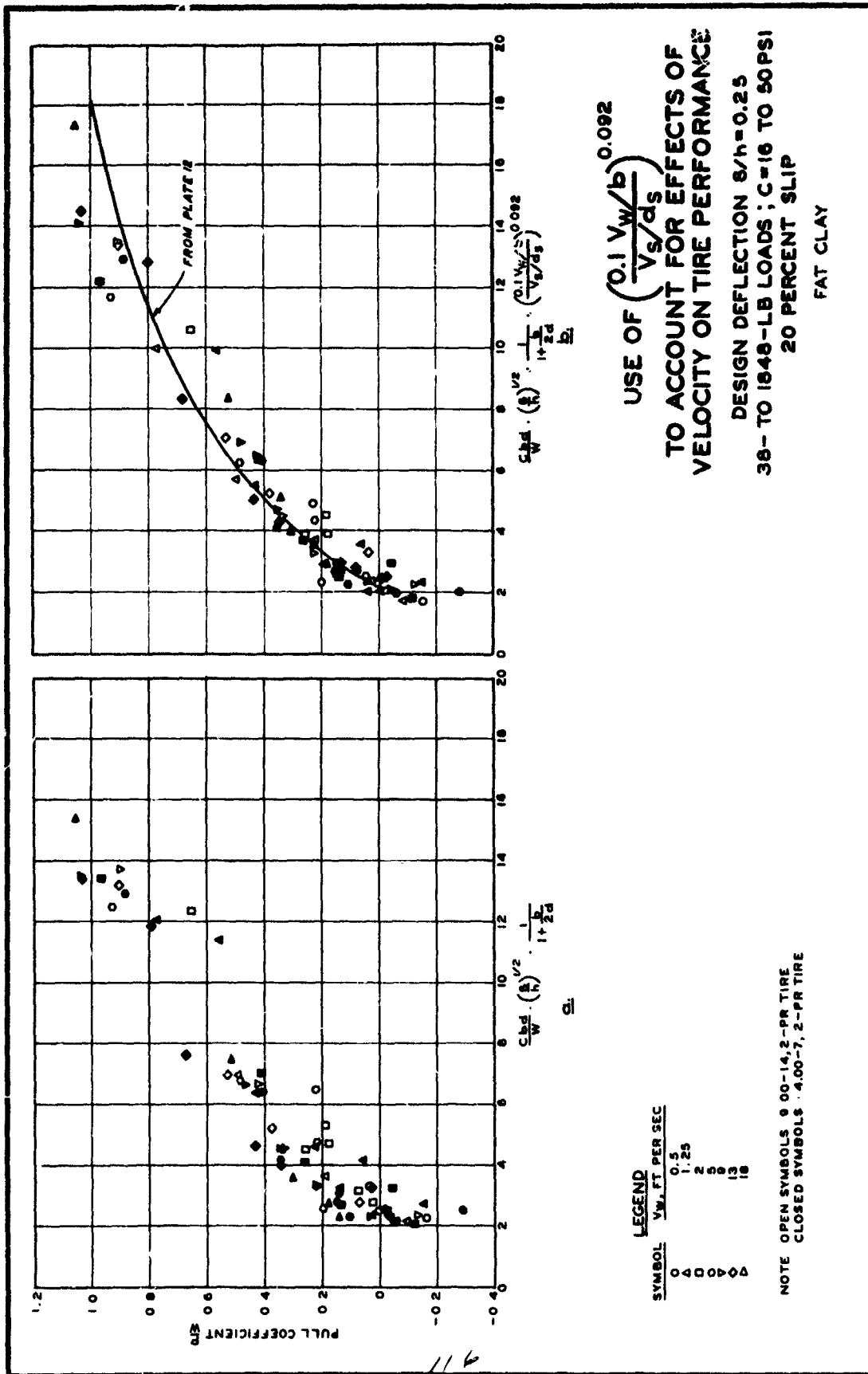
#### LEGEND

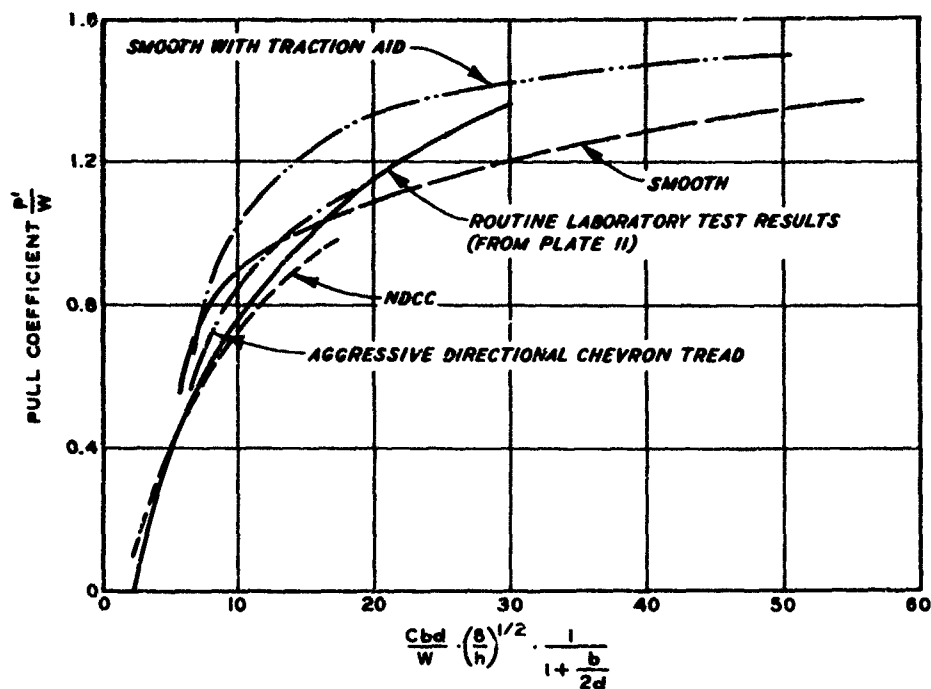
- 400-7, 2-PR
- △ 400-20, 2-PR
- 600-16, 2-PR
- 900-14, 2-PR
- ▽ 175-26, BICYCLE
- 16X6 50-8, 2-PR
- ▲ 16X11 50-6, 2-PR
- 16X15 00-6, 2-PR
- 26X16 00-10, 4-PR
- ◆ 31X15 50-13, 4-PR
- x 600-16, SOLID RUBBER

#### RELATION OF PULL COEFFICIENT TO ALTERNATIVE PREDICTION TERM $\frac{CA_c}{W}$

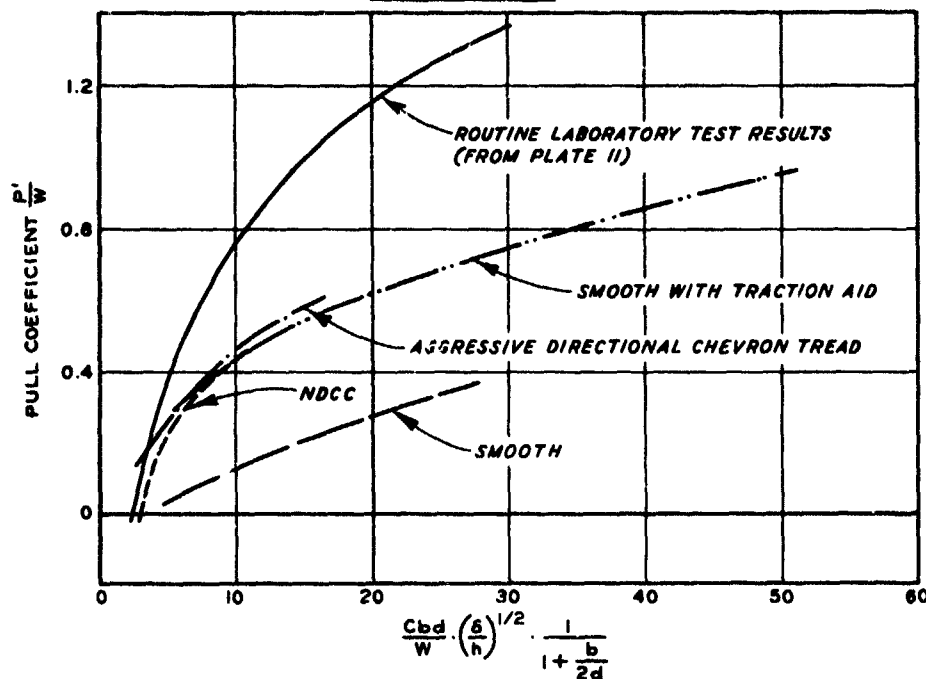
VALUES OF  $\delta/h$  FROM 0.01 TO 0.45,  
TWO TIRE SHAPES; 50- TO 1840-LB  
DESIGN WHEEL LOADS;  
C=8 TO 68 PSI  
FAT CLAY

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**a. UNFLOODED**



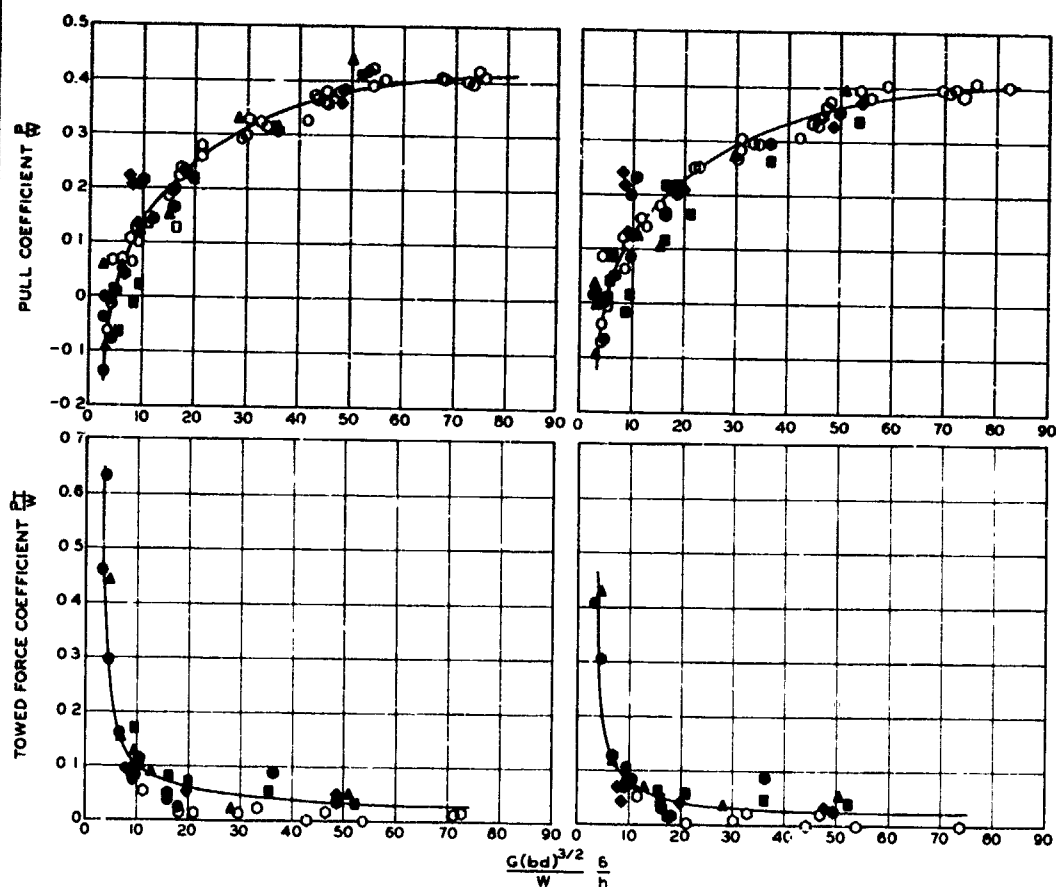
**b. FLOODED (DRAINED OR UNDRAINED)**

NOTE: MEASUREMENTS OF CONE INDEX C WERE OBTAINED IN THE 0- TO 1-IN-DEEP SOIL LAYER.

THE RELATIONS IN THIS PLATE WERE DEVELOPED FROM DATA PRESENTED IN TABLE 1 AND PLATE 8 OF REFERENCE 13

**INFLUENCE OF TIRE  
SURFACE AND SOIL  
SURFACE CONDITIONS**

**6.00-16 4-PR TIRE  
FIRST PASS, FAT CLAY**



a. SECOND PASS

b. THIRD PASS

**LEGEND**

- 4 00-7,2-PR
- 9 00-14,2-PR
- 16X6 50-8,2-PR
- ▲ 16X11 50-6,2-PR
- 16X15 00-6,2-PR
- 26X16 00-10,2-PR
- ◆ 31X15 50-13,2-PR

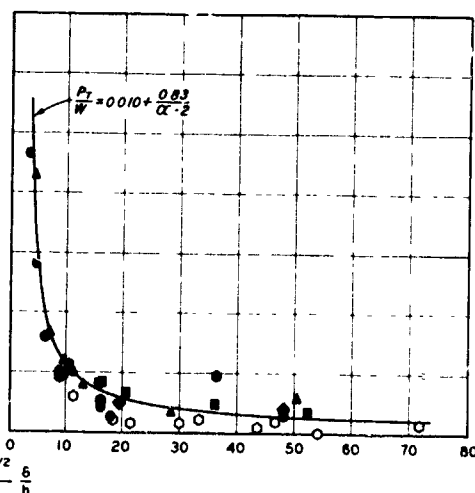
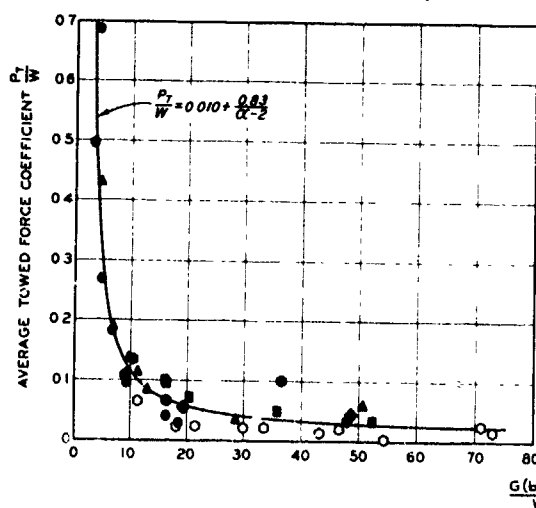
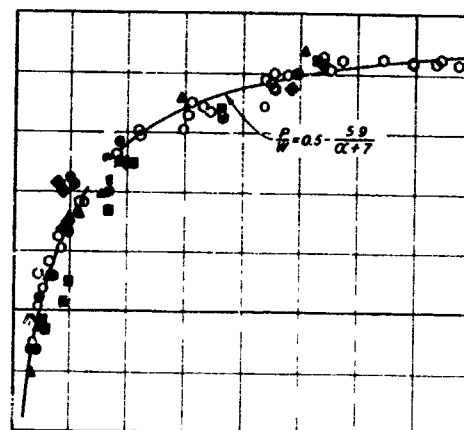
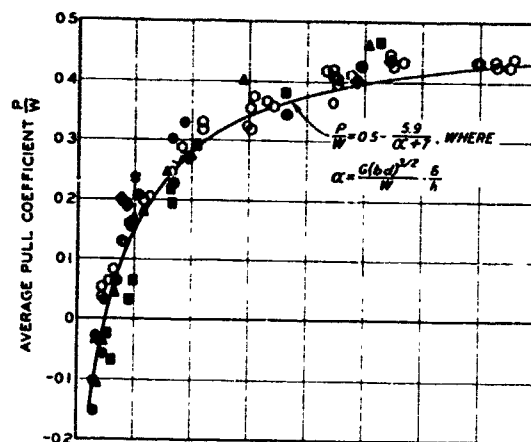
NOTE PENETRATION RESISTANCE  
GRADIENT G MEASURED  
BEFORE TRAFFIC

**RELATIONS OF PULL AND  
TOWED FORCE COEFFICIENTS  
TO BASIC PREDICTION  
TERM FOR SECOND AND  
THIRD PASSES**

VALUES OF  $b/h$  FROM 0.15 TO 0.35;  
44-TO 1350-LB DESIGN WHEEL LOADS;  
 $G = 3.2$  TO 20.2 PSI/IN.

YUMA SAND

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a AVERAGE DATA FROM FIRST  
AND SECOND PASSES

b AVERAGE DATA FROM FIRST,  
SECOND, AND THIRD PASSES

LEGEND

- 4 00-7, 2-PR
- 9 00-14, 4-PR
- 16X6 50-8, 2-PR
- ▲ 16X11 50-8, 2-PR
- 16X15 00-6, 2-PR
- 26X16 00-10, 2-PR
- ◆ 31X15 50-13, 2-PR

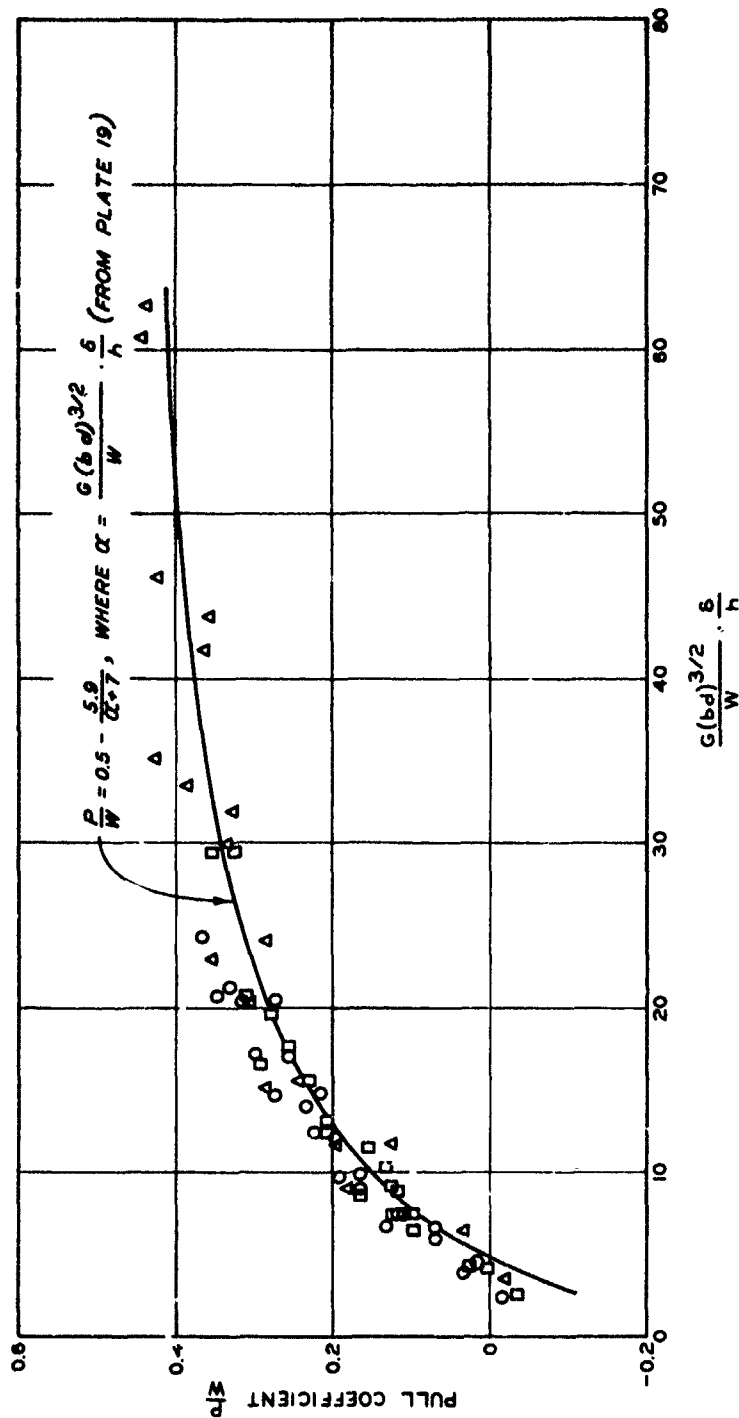
NOTE PENETRATION RESISTANCE GRADIENT  $G$   
MEASURED BEFORE TRAFFIC

AVERAGE PULL AND TOWED FORCE  
COEFFICIENTS VS BASIC  
PREDICTION TERM FOR SINGLE-  
WHEEL, MULTIPASS TESTS

VALUES OF  $b/h$  FROM 0.15 TO 0.35;  
44- TO 1340-LB AVERAGE WHEEL LOADS;  
 $G=3.2$  TO 20.2 PSI/IN.

YUMA SAND

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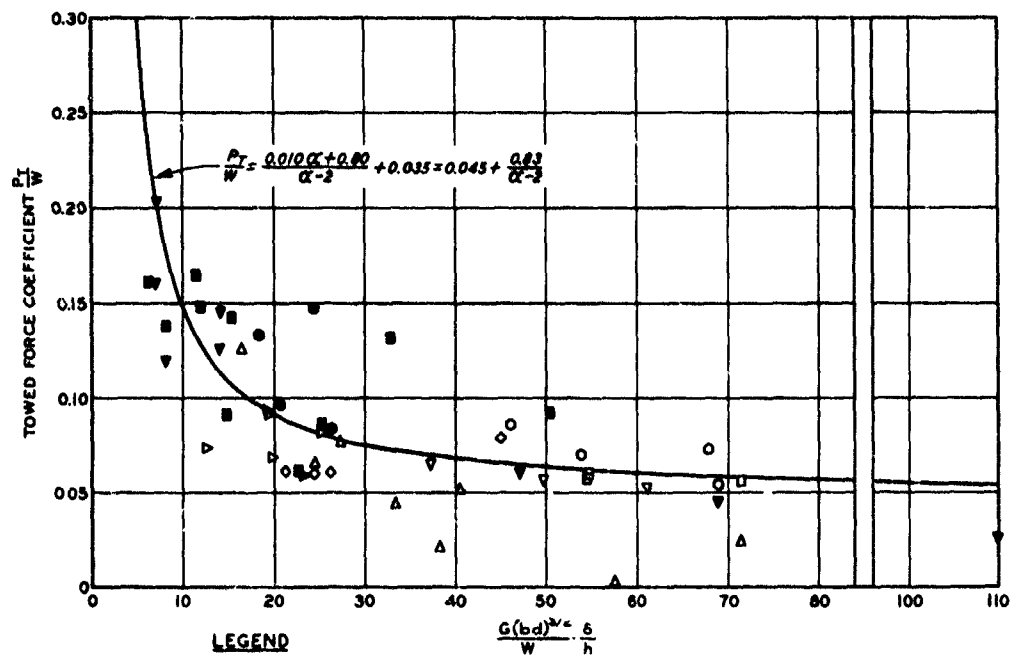
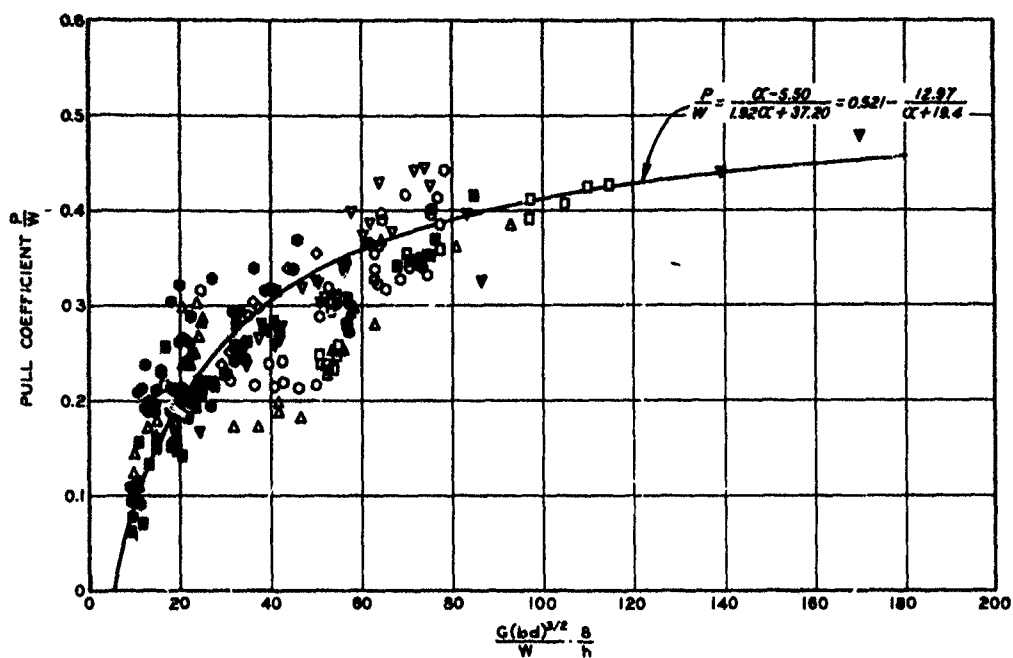


### LEGEND

VEHICLE	NOM TIRE SIZE	TREAD
○ M151	7.00-16	NDCC
△ M151	26X16.00-10	TERRA RIB
□ M37	8.00-16	NDCC

NOTE: PENETRATION RESISTANCE GRADIENT G MEASURED BEFORE TRAFFIC.

SINGLE-WHEEL AND  
FOUR-WHEEL-DRIVE  
VEHICLE PERFORMANCE  
LABORATORY TESTS  
YUMA SAND



#### LEGEND

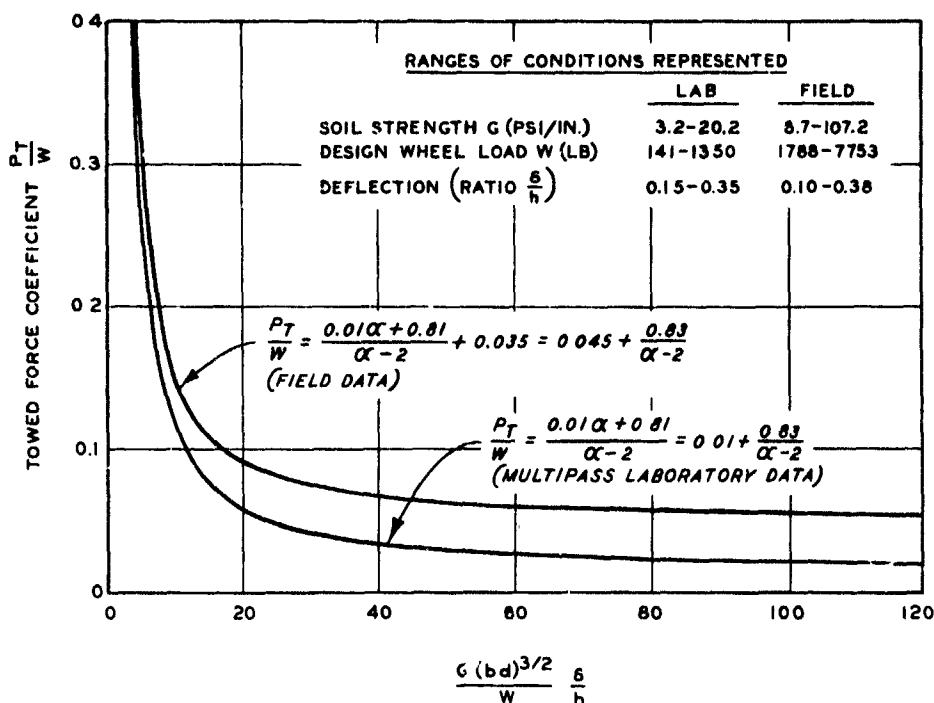
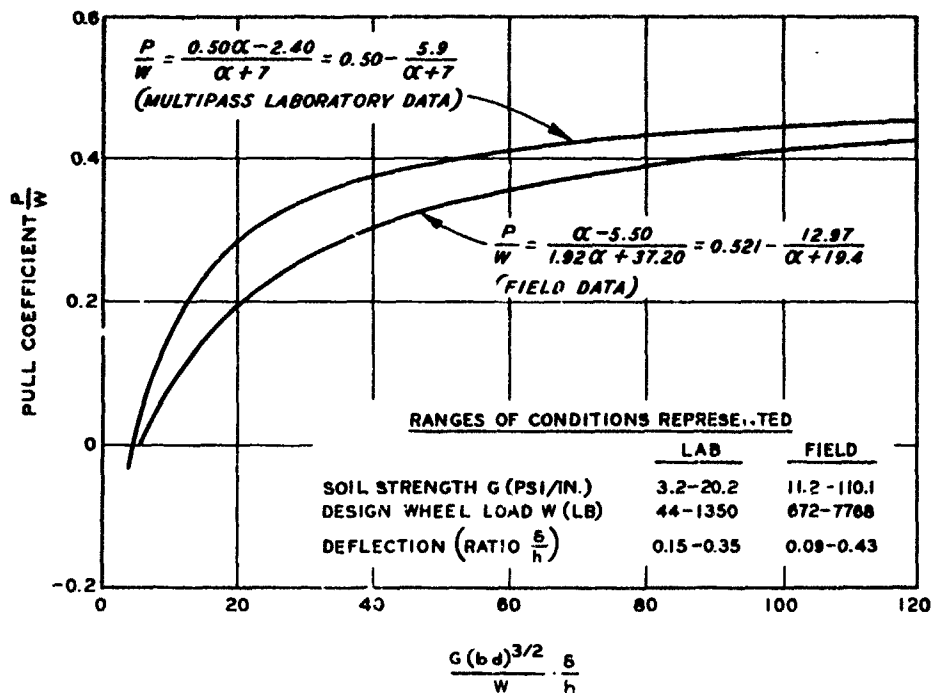
- M38A1, 4X4 (JEEP)
- △ M37, 4X4 TRUCK,  $\frac{3}{4}$ -TON
- M34 AND M135, 6X6 TRUCKS, 2½-TON
- DUKW 353, 6X6 TRUCK, 2½-TON
- ▽ M41, 6X6 TRUCK, 5-TON
- ◇ BUCKET LOADER, 4X4 TRACTOR
- TURNADOZER, 4X4 TRACTOR
- ▽ GOER, 4X4 CARGO CARRIER, 5-TON (18-26)
- GOER, 4X4 CARGO CARRIER, 5-TON (15-34)
- ▷ M135, 4X4 TRUCK, 2½-TON

NOTE:  $\alpha = \frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h}$

OPEN SYMBOLS: DATA FROM TESTS OF TWO-AXLE VEHICLES  
CLOSED SYMBOLS: DATA FROM TESTS OF THREE-AXLE VEHICLES.

#### WHEELED VEHICLE PERFORMANCE IN SAND FIELD TESTS

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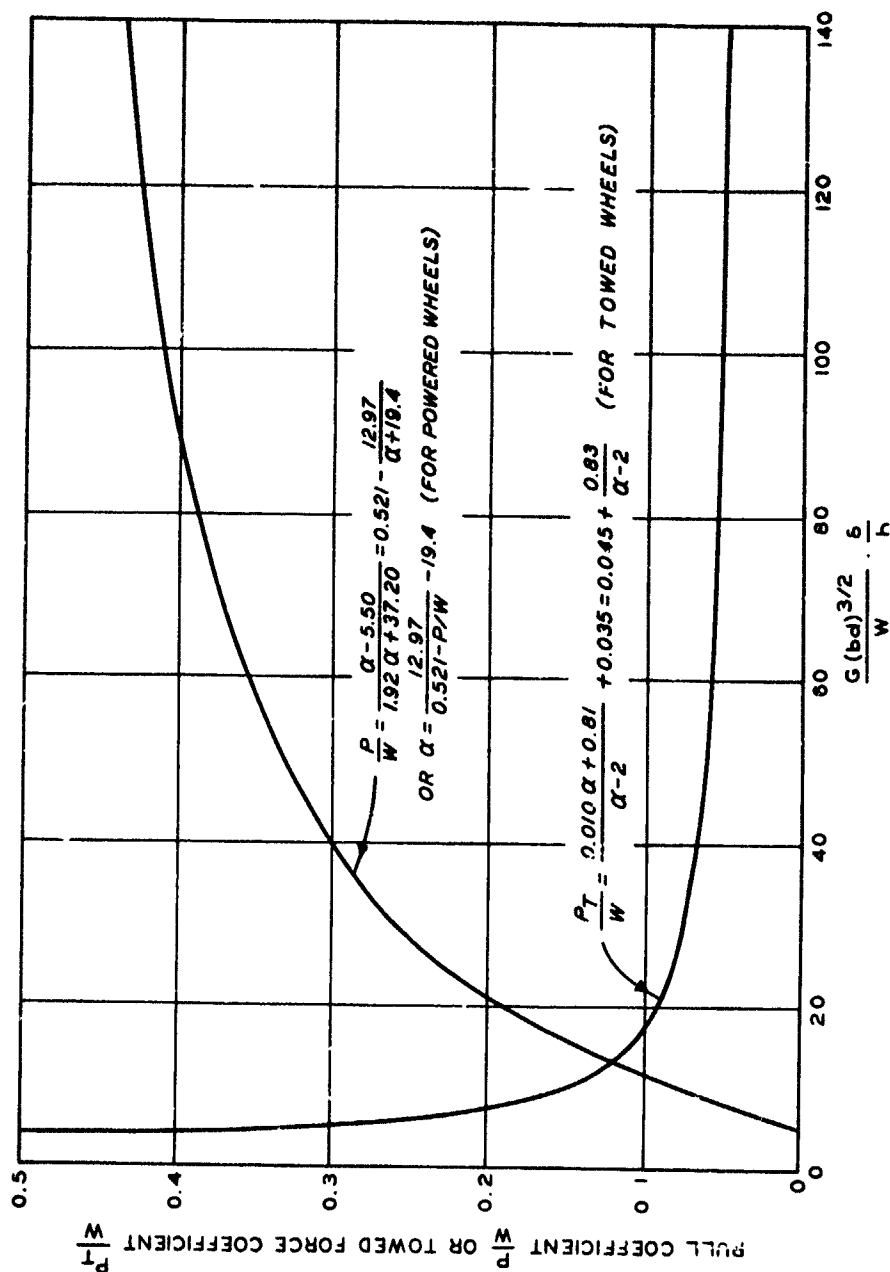


NOTE:  $\alpha = \frac{G(bd)^{3/2}}{W} \cdot \frac{s}{h}$

PENETRATION RESISTANCE  
GRADIENT  $G$  MEASURED  
BEFORE TRAFFIC.

LABORATORY AND FIELD  
PERFORMANCE DATA  
DRY-TO-MOIST SAND

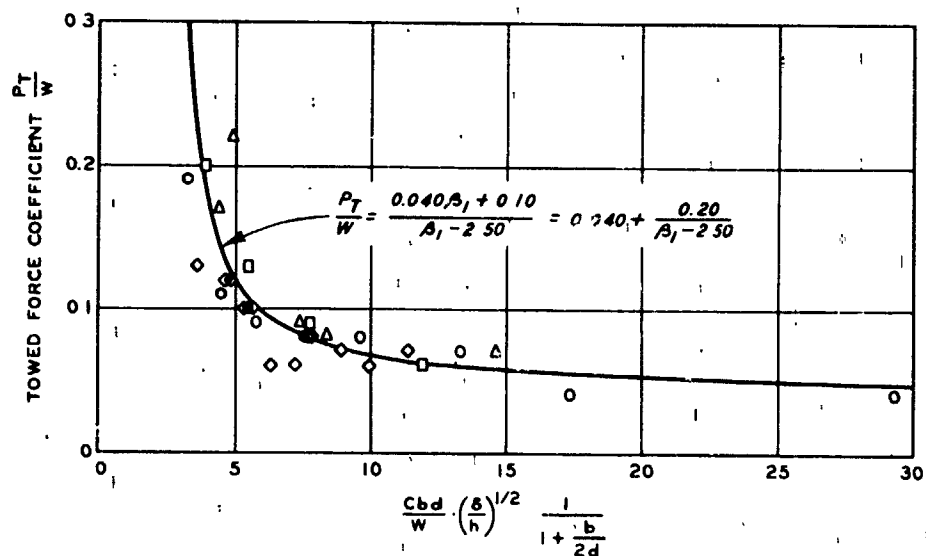
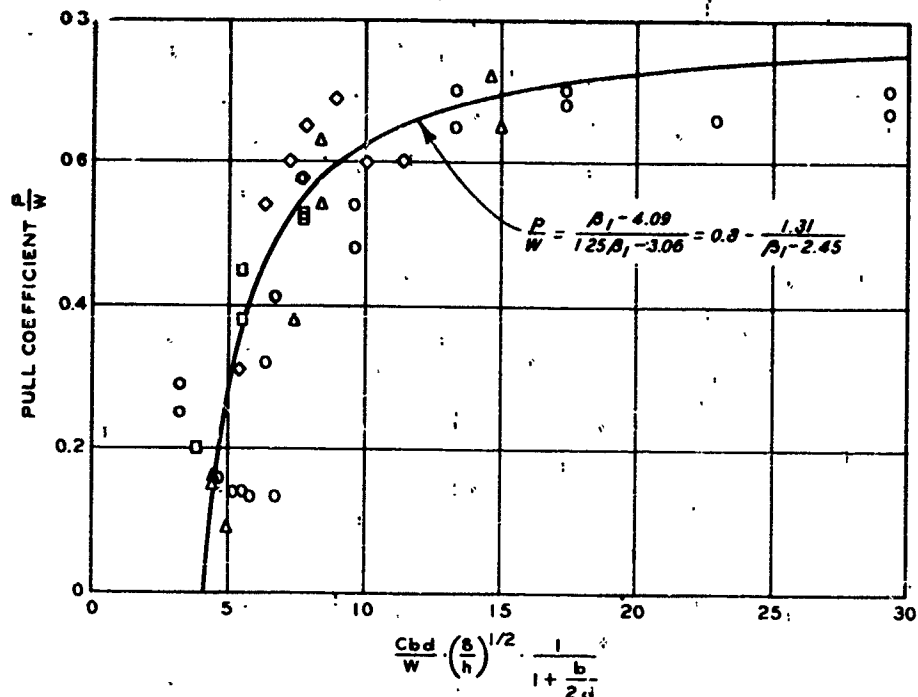
122



NOTE:  $\alpha = \frac{G(bd)^{3/2} \cdot s}{W \cdot h}$

PENETRATION RESISTANCE GRADIENT G  
MEASURED BEFORE TRAFFIC

PERFORMANCE  
PREDICTION CURVES  
WHEELED VEHICLES IN  
DRY-TO-MOIST SANDS



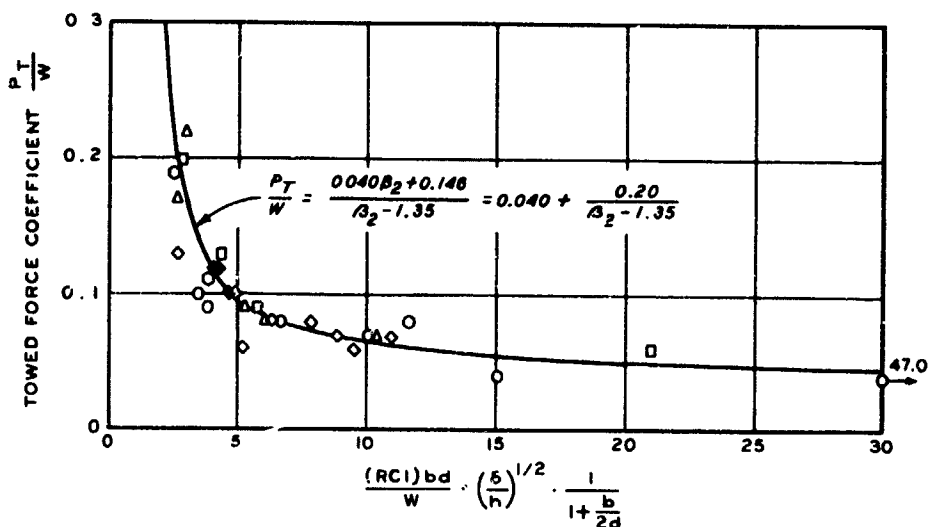
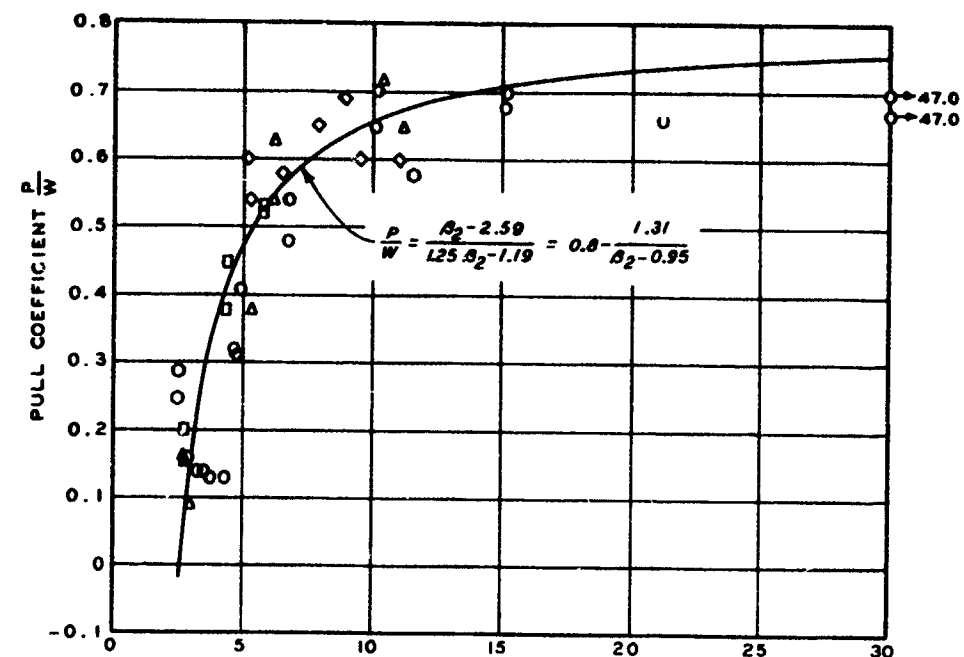
#### LEGEND

	NOM TIRE SIZE	VEHICLE
○	42X40-18	MEXA 10X10
△	48X31-18	MEXA 8X8
□	14 00-18, 6-PR	XM410E1
○	11 00-20, 12-PR	M95A2 (MOD)
◇	23 1-28, 10-PR	LOG SKIDDER

NOTE:  $\beta_1 = \frac{Cbd}{W} \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + \frac{b}{2d}}$

#### WHEELED VEHICLE PERFORMANCE IN WET, FINE-GRAINED SOILS FIELD TESTS

SOIL STRENGTH CHARACTERIZED BY  
BEFORE-TRAFFIC AVG CONE INDEX  
IN 0- TO 6-IN. LAYER



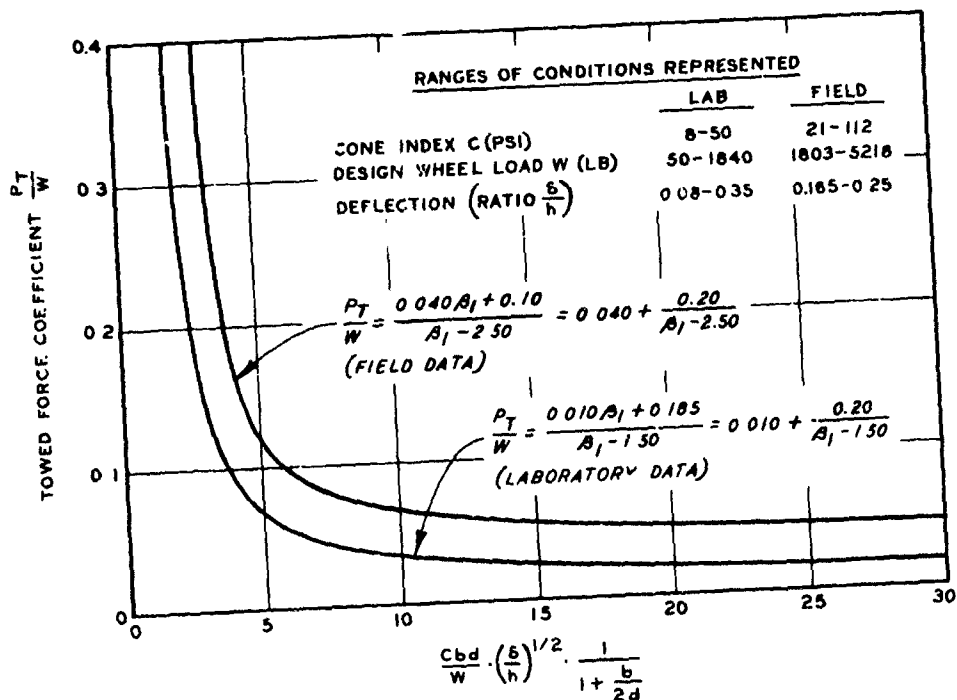
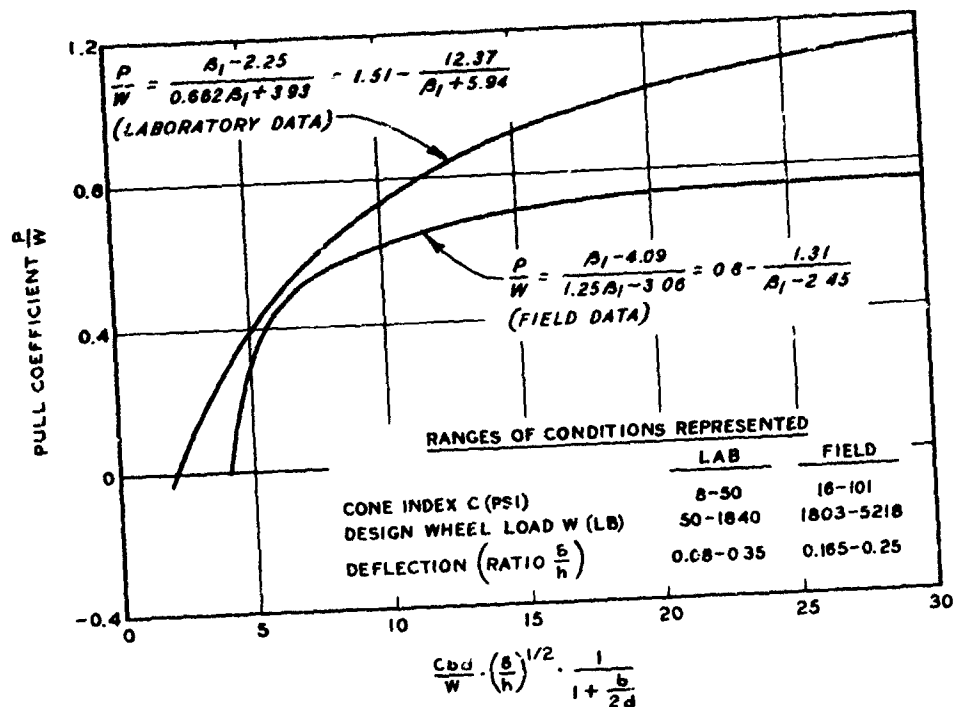
#### LEGEND

NOM TIRE SIZE	VEHICLE
1) 42 X 40-16	MEXA 10X10
2) 48 X 31-16	MEXA 8 X 8
3) 14.00-18, 6-PR	XM410E1
4) 11.00-20, 12-PR	M35A2(MOD)
5) 23 1-26, 10-PR	LOG SKIDDER

NOTE:  $B_2 = \frac{(RCI)bd}{W} \cdot \left(\frac{s}{h}\right)^{1/2} \cdot \frac{1}{1 + \frac{b}{2d}}$

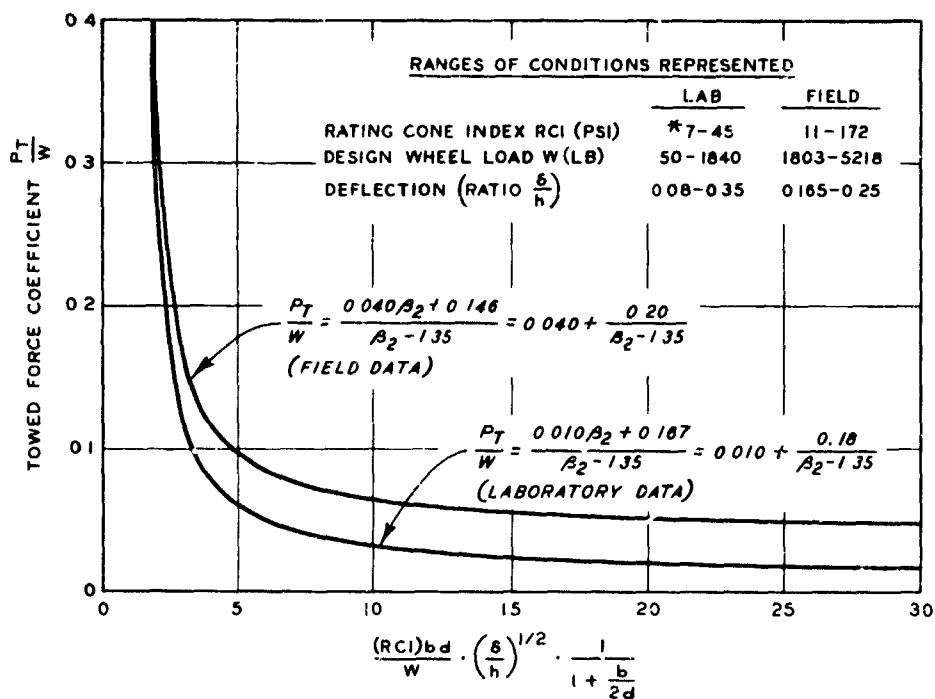
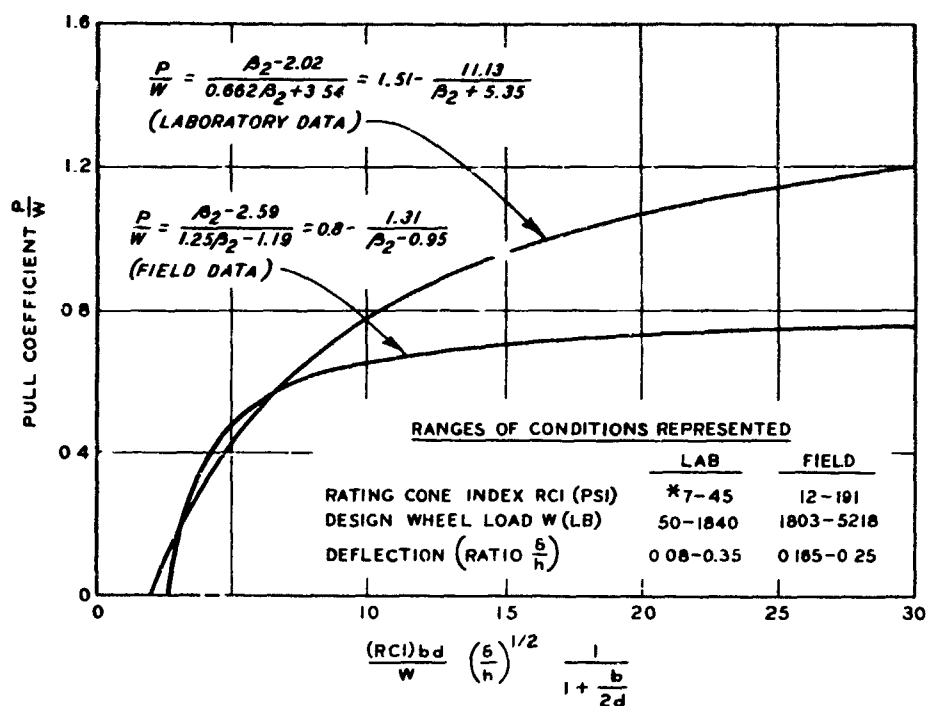
WHEELED VEHICLE  
PERFORMANCE IN WET,  
FINE-GRAINED SOILS  
FIELD TESTS  
SOIL STRENGTH CHARACTERIZED  
BY RATING CONF INDEX  
IN 0- TO 6-IN. LAYER

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NOTE:  $A_1 = \frac{Cbd}{W} \cdot \left(\frac{b}{h}\right)^{1/2} \cdot \frac{1}{1 + \frac{b}{2d}}$

COMPARISON OF  
LABORATORY AND FIELD  
PERFORMANCE RELATIONS  
WET, FINE-GRAINED SOILS  
SO'L STRENGTH CHARACTERIZED BY  
BEFORE-TRAFFIC AVG CONE INDEX  
IN 0- TO 8-IN. LAYER

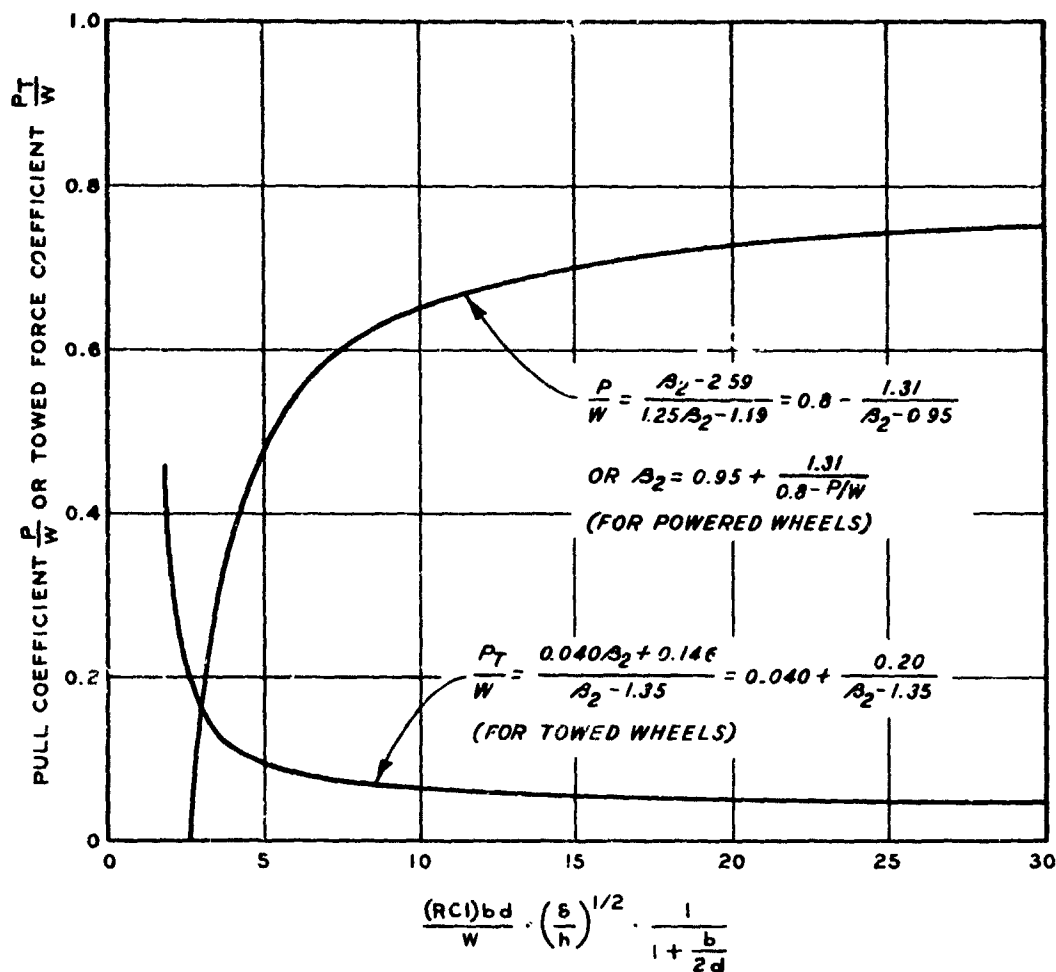


NOTE  $\beta_2 = \frac{(RCI)bd}{W} \left(\frac{\delta}{h}\right)^{1/2} \frac{1}{1 + \frac{b}{2d}}$

\* 0.90 TIMES MEASURED AVG CONE INDEX  
IN THE 0- TO 6-IN SOIL LAYER

COMPARISON OF  
LABORATORY AND FIELD  
PERFORMANCE RELATIONS  
WET, FINE-GRAINED SOILS  
SOIL STRENGTH CHARACTERIZED  
BY RATING CONE INDEX  
IN 0- TO 6-IN LAYER

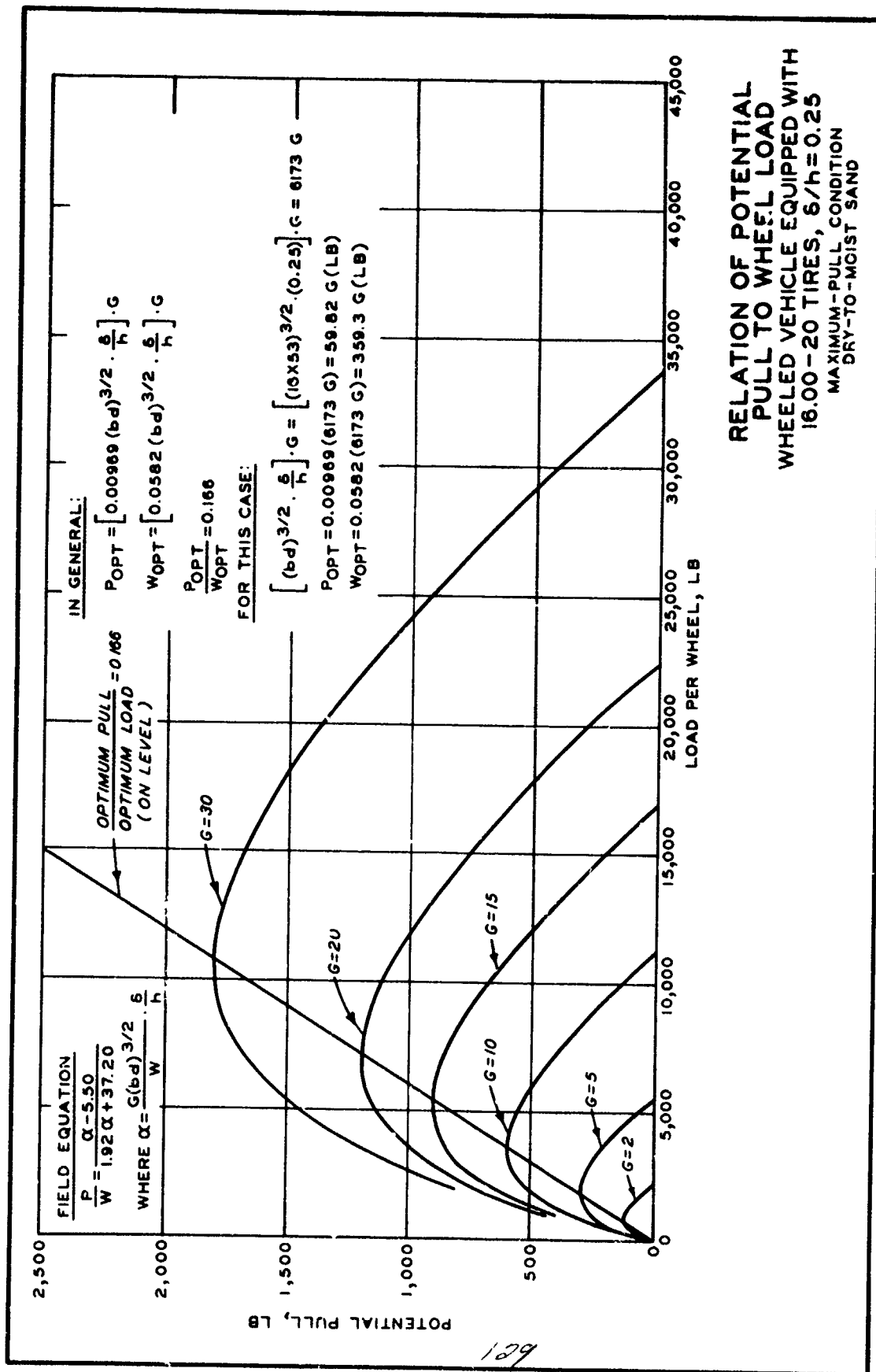
127

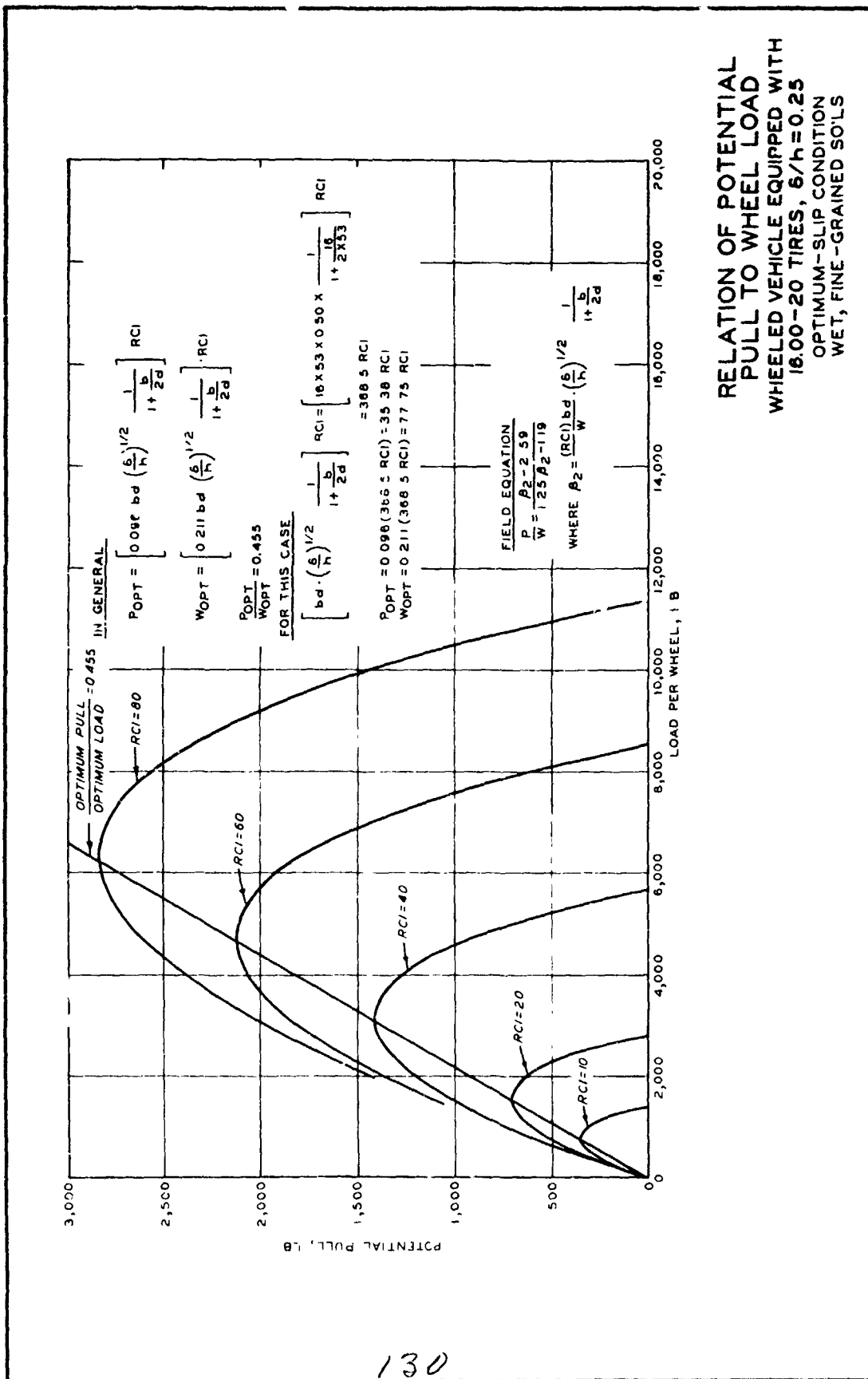


NOTE.  $A_2 = \frac{(RCI)bd}{W} \cdot \left(\frac{s}{h}\right)^{1/2} \cdot \frac{1}{1 + \frac{b}{2d}}$

# PERFORMANCE PREDICTION CURVES FOR WHEELED VEHICLES

WET, FINE-GRAINED SOILS  
OPTIMUM SLIP AND TOWED CONDITIONS





## APPENDIX A: MEASUREMENTS OF SAND STRENGTH, WHEEL PULL, AND TIRE SINKAGE

### Sand Strength

1. Penetration resistance gradient  $G$  is used in this report to characterize the strength of sand test beds, both in the laboratory and in the field. This term is defined as the gradient (or slope) of the penetration resistance (cone index) versus depth curve. For each WES laboratory wheel test in sand, the soil bed was constructed such that values of cone index increased linearly with depth, usually to about 11 or 12 in. (fig. 2a of main text); the value of  $G$  was then computed from cone index readings taken within this upper layer. Some evidence has been reported to indicate that the in-sand performance of a pneumatic tire is influenced by soil strength to a depth equal to the width of the tire;<sup>3\*</sup> no definite conclusion could be drawn from this brief study, however, because of the very limited range of values of the test parameters considered (only one tire size and one wheel load, for instance). This more recent idea regarding the sand depth of importance was preceded by a long history of measuring sand strength only in the upper 6-in. layer, both in the laboratory and in the field. (This statement needs clarification on two points: (a) Though  $G$  was computed and reported for many early laboratory tests only for the top 6-in. layer, the profile usually was constructed linearly to about 11 or 12 in., as in fig. 2a. (b) For many field tests, descriptions of the sand strength profile (either in terms of an average value of cone index, or individual cone index readings at prescribed increments of depth) are reported for other than the 0- to 6-in. layer; the 0- to 6-in. layer is by far the most common one reported, however.)

2. To allow sand strength data from a number of sources to be described on a common basis in this report, sand penetration resistance gradient  $G$  measured in the top 6-in. layer was chosen as the most

---

\* Superior numbers refer to similarly numbered items in Literature Cited at the end of the main text.

suitable parameter. Use of measurements from this layer is not intended to indicate that the 0- to 6-in. layer is the critical one for all sand-pneumatic tire situations. Furthermore, it is recommended that all laboratory sand test beds be constructed to provide linear strength profiles to the maximum depth practical, at least until the relation between critical depth and tire size, load, and deflection is definitely determined.

3. The next consideration after a common depth was a common means of defining penetration resistance gradient. In a number of early tests, the gradient was computed as

$$G' = \frac{\text{0- to 6-in. avg cone index}}{3 \text{ in.}} \quad (A1)$$

For a linear profile, the numerator of this term is the value of cone index at a depth of 3 in., and the value of the overall term equals the slope of a line drawn from the origin through the cone index reading at the 3-in. depth (fig. A1). Penetration resistance gradient defined in

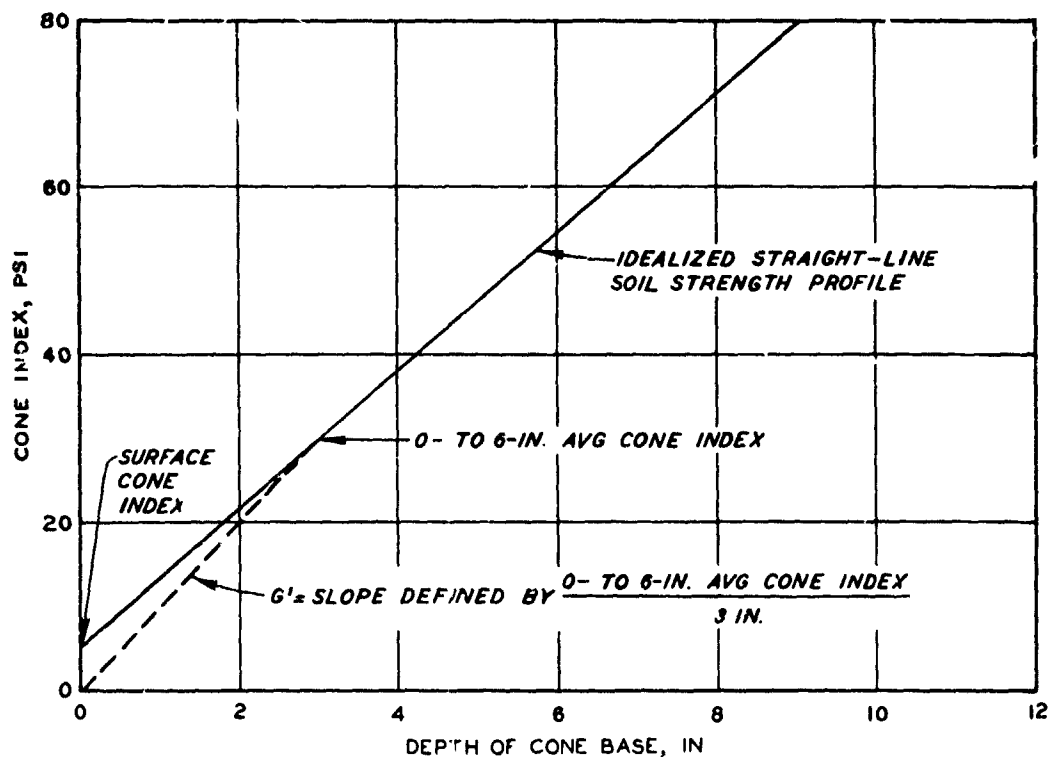


Fig. A1. Graphic illustration of  $G'$

this way is not the gradient of the cone index versus depth profile, and is characterized in this report as  $G'$ .

4. Values of penetration resistance gradient have also been reported based on the equation

$$G'_b = \frac{\begin{array}{c} \text{avg cone index to} \\ \text{depth equal to tire width} \\ \text{(to nearest inch)} \\ \hline \text{1/2 tire width} \\ \text{(to nearest inch)} \end{array}}{\quad} \quad (A2)$$

For a tire of approximately 6-in. width, this equation matches equation A1; for a given single soil strength profile, however, gradient defined by this equation scales the value of sand strength in inverse proportion to tire width (fig. A2). For no tire size does this equation measure the actual penetration resistance versus depth gradient; values obtained by its use are denoted in this report as  $G'_b$ .

5. The actual penetration resistance versus depth gradient can be

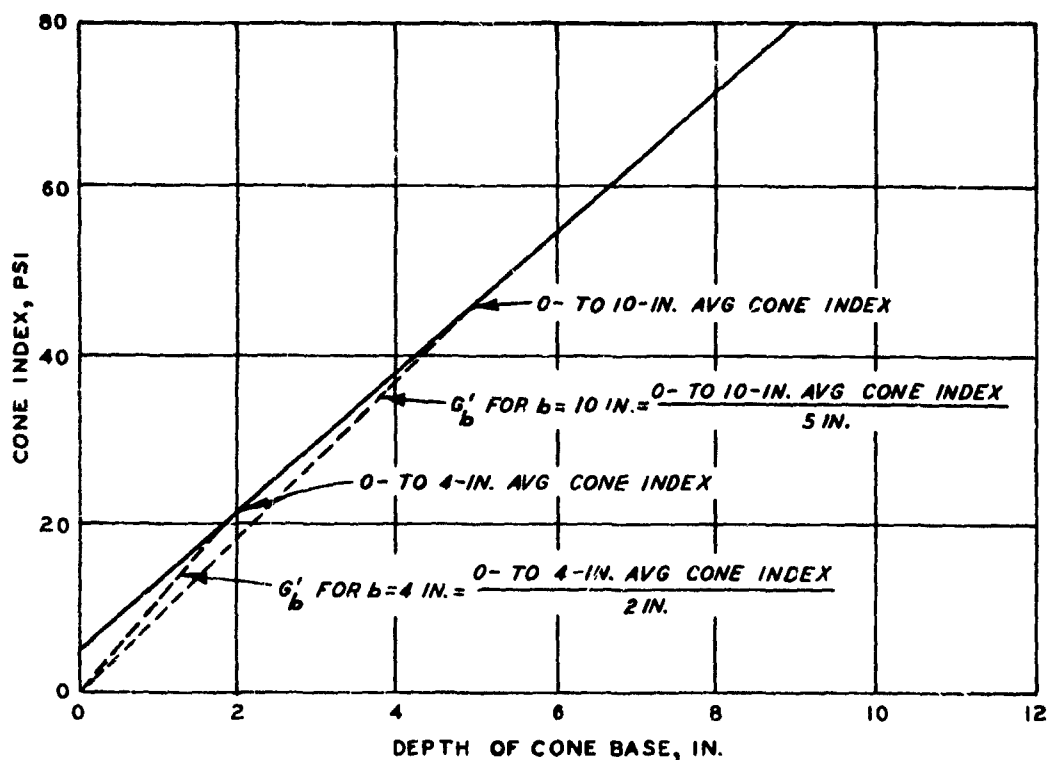


Fig. A2. Graphic illustration of  $G'_b$

adequately described for near-linear profiles by the relation

$$G = \frac{(\text{avg cone index over}) - (\text{surface})}{\text{depth of interest}} - \frac{(\text{cone index})}{1/2 \text{ depth of interest}} \quad (\text{A3})$$

Equation A3 matches equation A1, except that here the value of surface cone index is subtracted in the numerator to shift the lower end of the line defining  $G$  from the origin to the surface reading. Values of  $G$  were computed for the 0- to 6-in. layer in this report, either by direct application of equation A3 or by use of the relations of the following paragraph.

6. Since equations A1 and A3 differed only in that surface cone index was subtracted in the numerator of equation A3, the well-defined linear relation that exists between  $G'$  and  $G$  (fig. A3) was not unexpected. The linearity of the relation indicates that the value of surface cone index increases proportionately with an increase in the average value of cone index for the specified depth. The nearly identical slopes of the lines for the two sands (which have considerably different physical properties) indicate that this comparison between two techniques for quantifying sand strength was relatively unaffected by sand type. Values of 0- to 6-in. average cone index were available both for the field tests examined herein and for those tests whose sand strength was characterized by  $G'_b$  ( $G'_b$  values appear only in reference 2). These values were divided by 3 in. to obtain values of  $G'$ , and then multiplied by 0.8645 to obtain values of  $G$ . Values of  $G$  for all other sand tests reported herein were computed by equation A3, using individual soil strength profile values. For each test where  $G'$  (or 0- to 6-in. average cone index) or  $G'_b$  has been used in a previous report to describe soil strength, that value is listed in the appropriate table of this report, along with the value of  $G$  for the 0- to 6-in. layer. All terms that involve a measurement of sand strength in the main text of this report use only the value of  $G$ .

#### Wheel Pull

7. Wheel pull  $P$  is defined in reference 1 as "The component,

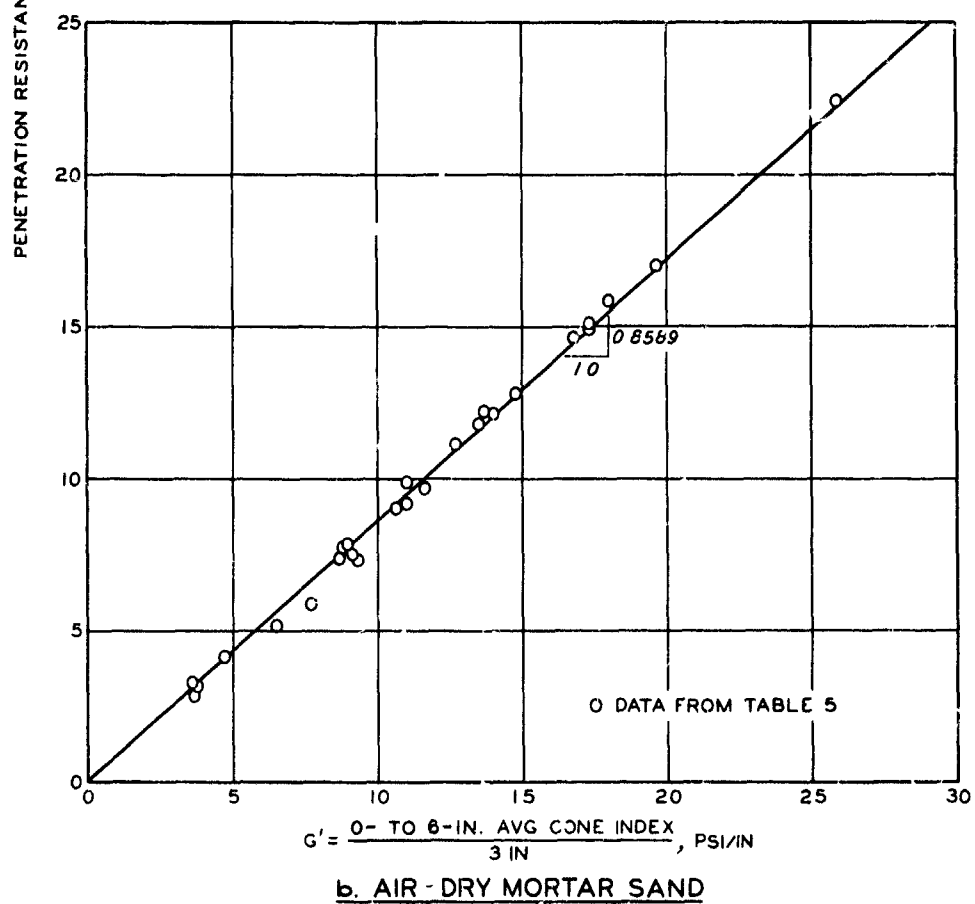
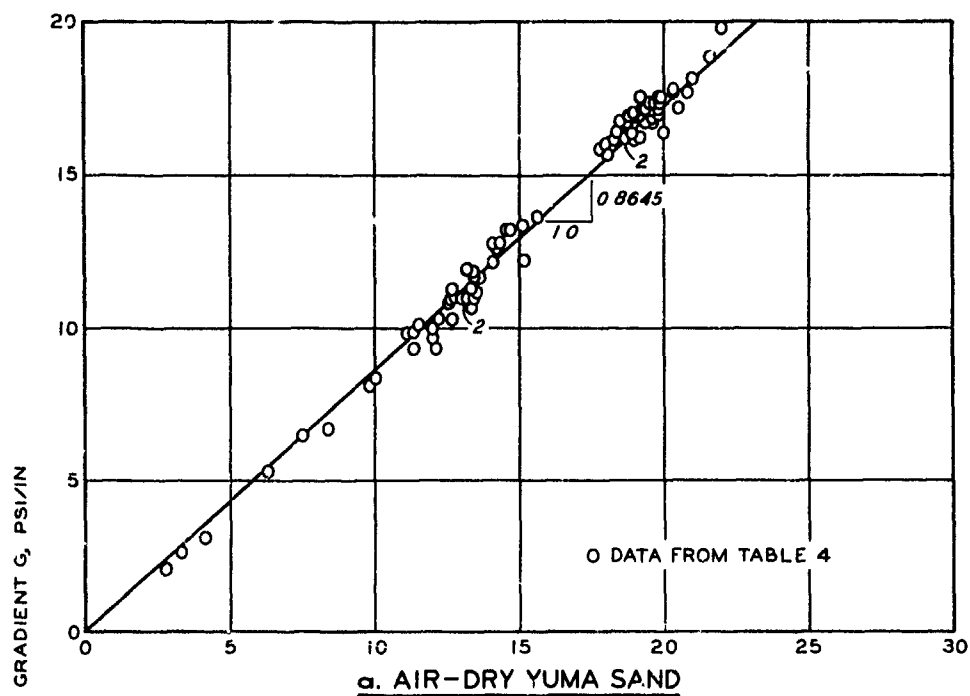


Fig. A3. Relations between  $G'$  and  $G$  for two sands

acting parallel to the direction of travel, of the resultant of all soil forces acting on the tire. It is considered to be positive when the tire is performing useful work, and to be negative when an external force must be applied to maintain motion...." In constant or near-constant slip tests, this parameter can be measured directly by a horizontally aligned force-measuring unit (a load cell, for example).

8. In programmed-increasing-slip tests of the type conducted at the WFS, wheel slip is made to increase linearly during the test by maintaining wheel rotational velocity constant and decreasing the dynamometer carriage translational velocity linearly from some maximum value to zero (fig. A4). Within the dynamometer carriage, the test wheel is mounted in a lower frame assembly (like that shown in fig. A5), which consists of an inner and an outer frame. The relative longitudinal movement between the inner and outer frames is opposed by a force cell

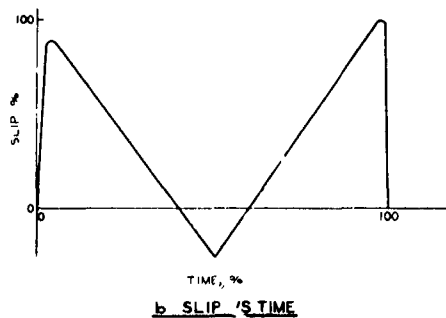
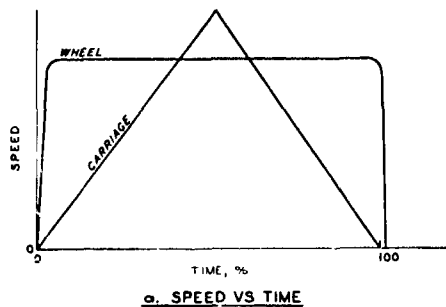
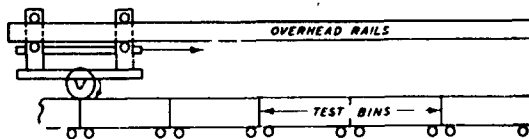


Fig. A4. Speed and slip diagrams for a programmed-increasing-slip test

mounted horizontally between the two frames, so that the reading from this cell is a measure of pull; a positive pull is indicated when the inner frame moves forward relative to the outer frame, and a negative pull for the opposite situation. The mass located within the inner frame (test wheel, axle, transmission, etc.) also contributes to relative movement between the inner and outer frames if this mass is either accelerated or decelerated. For the programmed-increasing-slip test, the carriage is uniformly decelerated, thereby contributing to the inner frame's being moved forward relative to the outer frame and producing a

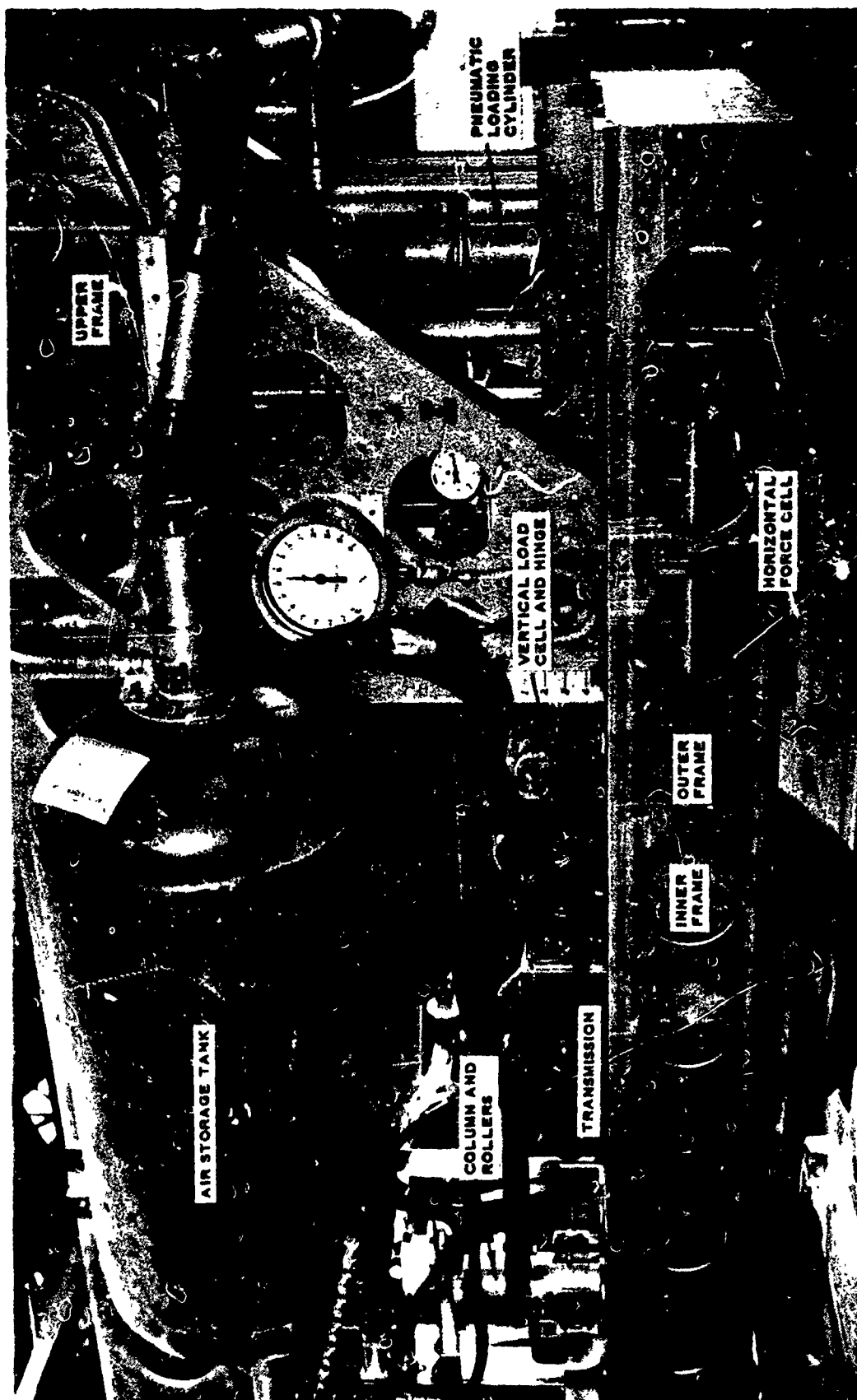
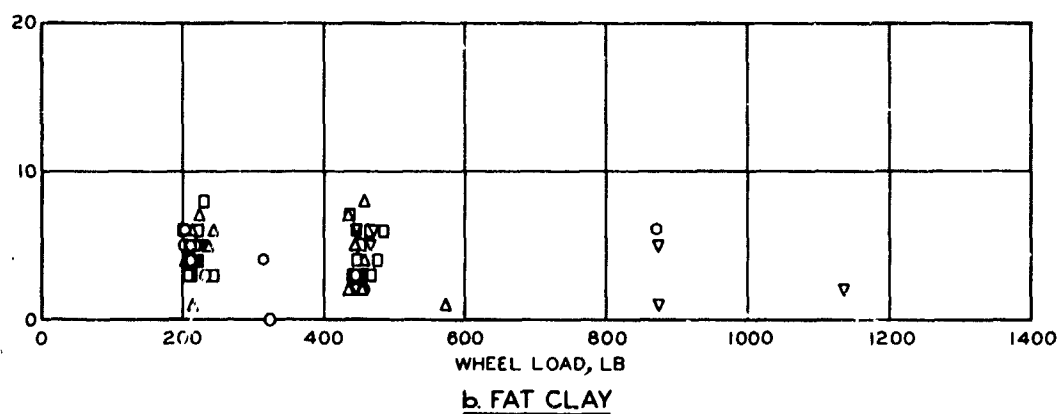
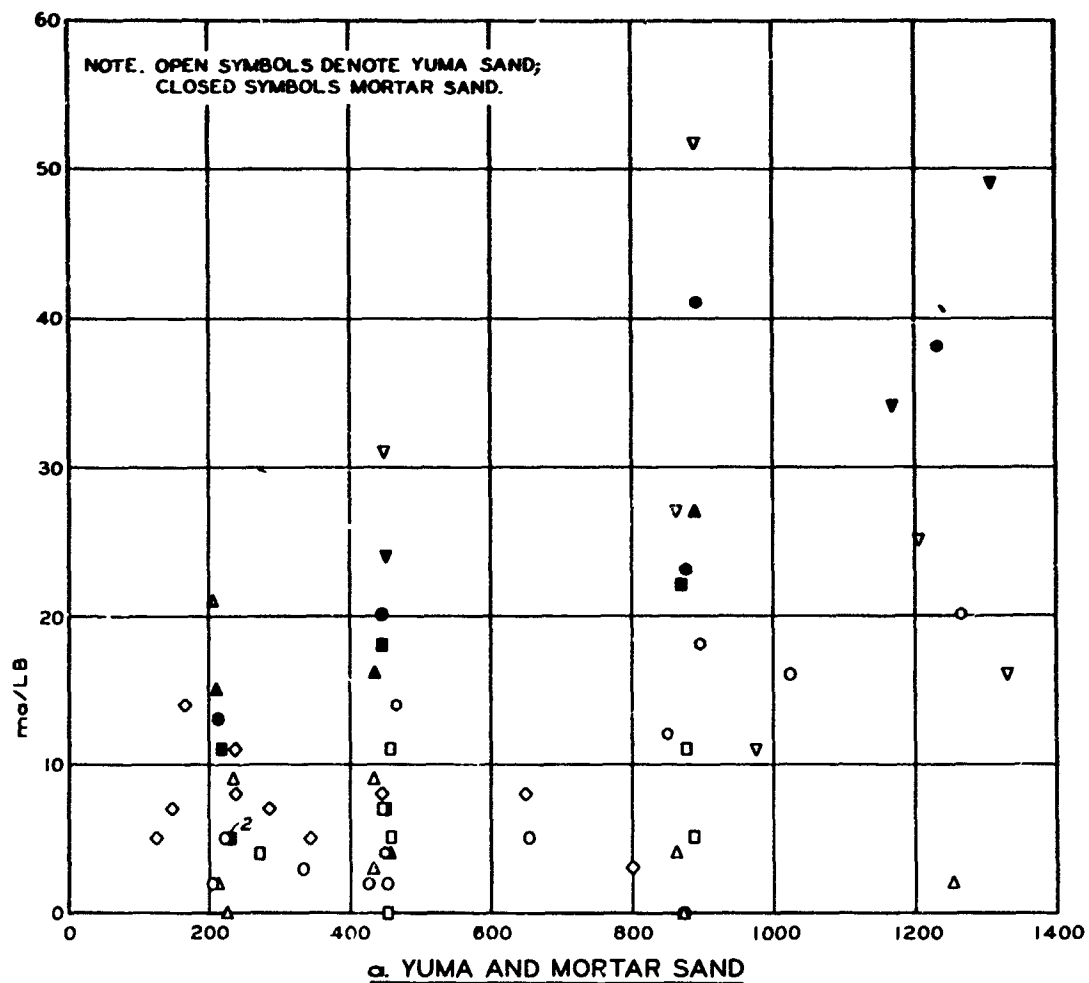


Fig. A5. Left side view of test carriage with wheel resting on launching platform

force of magnitude  $ma$  (mass times (negative) acceleration), which is recorded by the force cell as a positive pull. Thus, values of pull that are too large will be recorded in a programmed-increasing-slip test unless a correction is made to account for  $ma$ .

9. To obtain this correction, the dynamometer carriage is snatched in air prior to testing, and measurements are taken of (a) the value of acceleration (an accelerometer measures snatch-off acceleration, which value generally is taken several times larger than that encountered during the test), (b) the value of uncorrected wheel pull, and (c) the sum of (a) and (b). Each of quantities (a), (b), and (c) is recorded electrically; signals (a) and (b) are direct measurements, and signal (c) is an electrical sum of (a) and (b). The value of (c) changes in phase with quantity (a), carriage acceleration. The value of the effective mass contributing to  $ma$  is electrically solved for by changing potentiometer settings that control signal (c) until the value of signal (c) remains constant at the same value achieved before and after snatch-off, even under the action of peak acceleration. During testing, each signal (a), (b), and (c) is recorded. Signal (b), pull uncorrected for  $ma$ , is referred to in this report as  $P'$ ; and signal (c), pull corrected for  $ma$ , as  $P$ . (Pulls from constant or near-constant slip tests and from constant pull tests need no  $ma$  correction and are also referred to as  $P$ .)

10. The absolute magnitude of the  $ma$  force appears to be relatively small and fairly stable at about 0 to 8 lb for the 20 percent slip point in programmed-increasing-slip tests in the laboratory clay (fig. A6b).  $ma$  values of much larger average value and much greater dispersion were obtained at the 20 percent slip point in sand (fig. A6a). Unfortunately, the influence of  $ma$  on the pull signal in a programmed-increasing-slip test was not recognized in the early stages of testing, and WES reports prior to reference 6 reported values of  $P'$ , pull uncorrected for  $ma$ . The  $ma$  correction is influenced by changes in the value of  $m$  (differences in tire size, transmission used, etc.) and in the value of  $a$  (slight changes in carriage deceleration rate between tests). Even if these quantities were known precisely for tests not



**LEGEND**

- O 16X6 50-8, 2-PR
- Δ 16X11 50-6, 2-PR
- 16X15 00-6, 2-PR
- 26X18 00-10, 4-PR
- ▽ 31X15 50-13, 4-PR
- Δ 9 00-14, 2-PR

Fig. A6. Relation of  $ma$  to wheel load for pneumatic tires in sand and clay; 20 percent slip point; wheel speed = 5 ft/sec

instrumented to measure  $m_a$ , no well-defined correction could be made based on experience from tests in which both  $P'$  and  $P$  were recorded. Particularly for tires in sand, the  $m_a$  correction varied significantly between tests (fig. A6a) even though essentially the same values of  $a$  and pretest-measured  $m$  were acting. Fortunately, enough tests have been conducted in which corrected pull  $P$  was measured to develop the relations involving wheel pull in the main text of the report. Relations that use uncorrected pull  $P'$  (i.e.  $P + m_a$ ) are also reported herein, with the warning that relations based on  $P'$  predict algebraically larger-than-actual pull by a relatively small amount (estimated as 0 to 10 percent of wheel load for tires in sand, and 0 to 5 percent for tires in clay).

#### Tire Sinkage

11. It was demonstrated conclusively in Appendix A, "Sinkage Study," of reference 19 that the sinkage of a pneumatic tire can be accurately computed by the equation

$$z = \frac{2H(\delta_{HS} + H)^2}{H^2 + (\delta_{HS} + H)^2} \quad (A4)$$

where

$z$  = pneumatic tire sinkage

$H$  = vertical hub movement

$\delta_{HS}$  = deflection of a pneumatic tire loaded on a hard surface

Except for tests whose data were taken from reference 2, all sinkage values reported herein were computed by the above equation. Sinkage values in reference 2 were computed by the equation

$$z = H + (\delta_{HS} - \delta_{IS}) \quad (A5)$$

where

$z$ ,  $H$ , and  $\delta_{HS}$  are defined above

$\delta_{IS}$  = in-soil deflection

Both  $\delta_{HS}$  and  $\delta_{IS}$  are measured directly beneath the wheel axle.

Equations A4 and A5 produce almost identical results for sinkages of important size (say, 1 in. and larger). Equation A4 is preferred, since it defines  $z$  accurately in terms of only two easily measured tire parameters,  $H$  and  $\delta_{HS}$ . Equation A5 requires these two parameters plus  $\delta_{IS}$ , a parameter far more difficult to measure and one much more susceptible to instrumentation error.

## APPENDIX B: TIRE SELECTION AND PREDICTION OF PERFORMANCE

1. The relations of the pull and towed force coefficients for wheeled vehicles to the basic prediction terms for sand and for clay (plates 23 and 28, respectively) offer the basis for a tentative performance prediction system and for design criteria for wheeled vehicles operating in dry-to-moist, coarse-grained soils and wet, soft, fine-grained soils. The curves in plates 23 and 28 can be used to forecast the mobility of existing vehicles or to select tires that will provide the desired degree of mobility for existing or proposed vehicles. These curves should be used with caution because (a) research effort to date has not quantified the effects of a number of factors that influence wheel performance significantly (principally those in paragraphs 52-58 of the main text), and (b) the precision of applicability of the relations in plates 23 and 28 is of the order indicated by the data scatter in plates 21 and 25, respectively, for vehicles operating under carefully controlled conditions in the field.

2. Quantitative relations like those in plates 23 and 28 are necessary for rational selection of tires; however, this choice must remain something of an art, since the tire designer must consider tradeoffs among a number of considerations (tire flexibility, durability, and stability; ground clearance; height of cargo bed; etc.) that apply to the particular problem at hand. One important consideration that applies to practically all off-road operations is that tire deflection should be maintained at as large a value as practicable (paragraphs 82 and 86 of the main text). This implies that tires should be as flexible relative to the loads they will be required to carry as safe operating conditions will allow.

3. The following examples illustrate a few of the many possible practical uses of the relations in plates 23 and 28. In each example, each tire is assumed to carry an equal share of the vehicle load. Also, the tangent of the maximum slope climbable is assumed to be practically equivalent numerically to maximum pull coefficient. The basis for this assumption is given in reference 20; field tests conducted since that

time have generally verified this assumption.

Example 1: Computation of Maximum Pull Coefficient and  
Slope Negotiable

4. If soil type and strength, wheel load, and tire dimensions are given, maximum drawbar pull or slope-climbing ability can be computed as shown in the calculations that follow.

a. Given.

Soil type, dry-to-moist sand

Soil strength  $G = 20$  psi in.

M135, 6x6, 2-1/2-ton truck

Gross vehicle weight  $nW = 18,000$  lb

Number of wheels  $n = 6$

Wheel load  $W = 3000$  lb

11.00-20 single tires,

$b = 11.0$  in.,  $d = 42.0$  in.,  $(bd)^{3/2} = 9800$  in.<sup>3</sup>,

$\delta/h = 0.35$

b. Find.

Maximum pull coefficient and slope negotiable.

c. Solution.

$$\alpha = \frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h} = \frac{20(9800)}{3000} \cdot 0.35 = 22.9$$

From plate 23, find  $P/W$  between 0.21 and 0.22, or use the equation for powered wheels in plate 23:

$$\frac{P}{W} = \frac{\alpha - 5.50}{1.92\alpha + 37.20} \quad (\text{equation 1; main text})$$

$$\frac{P}{W} = \frac{22.9 - 5.50}{1.92(22.9) + 37.20} = 0.214$$

d. Conclusion.

If a safety factor of 1.0 is assumed, this vehicle, under the conditions specified, can climb a 21.4 percent slope; or on level ground, it can tow an object whose resistance does not exceed 21.4 percent of the weight of the prime mover. Also, slope and maximum drawbar pull can be considered as additive; e.g. on a 10 percent slope, the

vehicle can pull a trailer whose rolling resistance does not exceed 11.4 percent of the vehicle's weight.

Example 2: Selection of Tire Sizes for Given Conditions

5. For a particular vehicle, equation 6 in the main text and plate 28 can be manipulated to solve for tire size required when the soil type and minimum soil strength, allowable tire deflection, design wheel load, and required slope-climbing ability or drawbar pull are known.

a. Given..

Soil type: soft, homogeneous, fat clay

Soil strength RCI (minimum) = 40

Slope = 20 percent

6x6 vehicle, single tandem tires

Gross vehicle weight  $nW = 25,200$  lb

Number of wheels  $n = 6$

Wheel load  $W = 4200$  lb

Maximum allowable tire deflection  $\delta/h = 0.35$

b. Find.

Tire sizes compatible with the given conditions.

c. Solution.

$$\beta_2 = \frac{(RCI)bd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)} = \frac{(RCI)}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{2bd^2}{2d + b} \quad (\text{equation 6; main text})$$

$$\frac{2bd^2}{2d + b} = \beta_2 \cdot \frac{W}{(RCI)} \cdot \frac{1}{(\delta/h)^{1/2}}$$

$$\beta_2 = \frac{2.59 - (1.19P/W)}{1 - (1.25P/W)}$$

$$\frac{2bd^2}{2d + b} = \frac{2.59 - 1.19(0.20)}{1 - 1.25(0.20)} \cdot \frac{4200}{40} \cdot \frac{1}{0.592} = 556 \text{ in.}^2$$

d. Tire selection.

Try 11.00-20, 2-PR, nondirectional, cross-country:

$b = 11.0$  in.,  $d = 12.0$  in., and  $2bd^2/(2d + b) = 409$ .

409 < 556 ; tire is inadequate.

Try 14.00-20, 12-PR, nondirectional, cross-country:

$b = 14.0 \text{ in.}$ ,  $d = 48.0 \text{ in.}$ , and  $2bd^2/(2d + b) = 586$  .

586 > 556 ; tire is adequate.

Try 46x18-20, 8-PR:  $b = 19.5 \text{ in.}$ ,  $d = 45.5 \text{ in.}$ , and

$2bd^2/(2d + b) = 731$  .  $731 > 556$  ; tire is adequate.

e. Conclusion.

In the foregoing example, only two tires, the 14.00-20 and the 46x18-20 tires, were demonstrated to be adequate; obviously, there are many tires that fulfill the requirements from a mobility standpoint. The designer should consider, too, that changes in tire diameter  $d$  affect values of  $2bd^2/(2d + b)$  more than corresponding relative changes in width  $b$  (fig. 11, main text). From a practical point of view, however, proportionate increases can be achieved far more readily for tire width than for diameter, e.g. it was reasonable to consider increasing width from 11.0 to 19.5 in. in the example above (a 77 percent increase) while changing diameter only nominally; it would be impractical for most vehicle configurations to hold width at approximately 11.0 in. and increase diameter from 42 to 74 in. (a 77 percent increase).

Example 3: Computation of Maximum (Immobilization) Load  
and Maximum Weight Pullable

6. If soil type and strength, wheel load, and tire dimensions are known, the maximum load that a given vehicle can carry without immobilization and the maximum trailer weight that it can pull on level ground can be determined in calculations like those below.

a. Given.

Soil type: soft, wet, homogeneous, fat clay

Soil strength  $RCI = 30$

M135, 6x6, 2-1/2-ton truck

Gross vehicle weight  $nW = 18,000 \text{ lb}$

Number of wheels  $n = 6$

Wheel load  $W = 3000$  lb

11.00-20 single tires:

$$b = 11.0 \text{ in.}, d = 42.0 \text{ in.}, bd = 462 \text{ in.}^2,$$

$$\delta/h = 0.35$$

b. Find.

Maximum allowable wheel load and wheel load to develop maximum pulling ability.

c. Solution.

$$\frac{P}{W} = \frac{\beta_2 - 2.59}{1.25\beta_2 - 1.19}, \text{ where } \beta_2 = \frac{(RCI)bd}{W} \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)} \text{ (from plate 28 and equation 6 in main$$

text). For  $P/W = 0$ ,  $\beta_2 = 2.59$  and immobilization load

$$W_I = \left[ (RCI) \cdot bd \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)} \right] \div 2.59$$
$$W_I = \left[ (30 \cdot 11.0 \cdot 42.0) \cdot \sqrt{0.35} \cdot \frac{1}{1 + (11.0/84.0)} \right]$$
$$\div 2.59 = 2800 \text{ lb (per wheel)}$$

From plate 30,

$$W_{opt} = 0.211 \left[ bd \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)} \right] \cdot (RCI)$$
$$W_{opt} = \left[ 0.211 \cdot 11.0 \cdot 42.0 \cdot \sqrt{0.35} \cdot \frac{1}{1 + (11.0/84.0)} \right]$$
$$\cdot 30 = 1530 \text{ lb (per wheel)}$$

From equation 9 in the main text,

$$P_{opt} = 0.096 \left[ bd \cdot \left(\frac{\delta}{h}\right)^{1/2} \cdot \frac{1}{1 + (b/2d)} \right] \cdot (RCI) = 696 \text{ lb}$$

(per wheel) = maximum weight pullable by each wheel on level ground.

d. Conclusion.

The range of values of load between zero pull and optimum pull (in terms of its absolute value) for the conditions specified is 2800 to 1530 lb per wheel. Values of

pull/load (but not absolute pull) are increased by reducing wheel load below optimum load; thus, the value of slope negotiable ( $\approx P/W$ ) would be improved by reducing wheel load as much as possible.

Example 4: Determination of Mobility of a Vehicle-Trailer Combination

7. If the minimum soil strength, maximum slope, and required vehicle and trailer data are known, the mobility of the vehicle-trailer combination can be estimated by the relations in plate 23. The procedure to be followed is illustrated below.

a. Given.

Soil type: air-dry sand

Soil strength  $G$  (minimum) = 20

Slope (maximum) = 10 percent

M37, 4x4, 3/4-ton truck

Gross vehicle weight  $nW = 6000$  lb

Number of wheels  $n = 4$

Wheel load  $W = 1500$  lb

9.00-16 tires:

$$b = 9.2 \text{ in.}, d = 34.0 \text{ in.}, (bd)^{3/2} = 5530 \text{ in.}^3,$$

$$\delta/h = 0.35$$

M101, 2-wheel trailer

Gross trailer weight  $nW = 2000$  lb

Number of wheels  $n = 2$

Wheel load  $W = 1000$  lb

9.00-16 tires:

$$b = 9.2 \text{ in.}, d = 34.0 \text{ in.}, (bd)^{3/2} = 5530 \text{ in.}^3,$$

$$\delta/h = 0.35$$

b. Find.

Is the vehicle-trailer combination mobile under the conditions specified?

c. Solution.

(1) For pull of prime mover:

$$\alpha = \frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h} = \frac{20(5530)}{1500} \cdot 0.35$$

$$\alpha = 25.8$$

From plate 23, find  $P/W = 0.24$ . Use the equation for powered wheels in plate 23:

$$\frac{P}{W} = \frac{\alpha - 5.50}{1.92\alpha + 37.20} \quad (\text{equation 1; main text})$$

$$\frac{P}{W} = \frac{25.8 - 5.50}{1.92(25.8) + 37.20} = 0.234$$

$$\begin{aligned} \text{Maximum drawbar pull on level ground} &= \frac{P}{W} \cdot (nW) \\ &= 0.234(6000 \text{ lb}) = 1400 \text{ lb} \end{aligned}$$

- (2) Maximum drawbar pull of prime mover on 10 percent slope:

$$\begin{aligned} &\text{Maximum pull of M37 on 10 percent slope} \\ &= \left( \frac{P}{W} - \text{slope} \right) (nW) = (0.234 - 0.100)(6000 \text{ lb}) \\ &= 800 \text{ lb} \end{aligned}$$

- (3) Trailer rolling resistance (level surface):

$$\alpha = \frac{G(bd)^{3/2}}{W} \cdot \frac{\delta}{h} = \frac{20(5530)}{1000} \cdot 0.35 = 38.7$$

From plate 23,  $P_T/W = 0.06$ ; or from the equation for towed wheels in plate 23:

$$\begin{aligned} P_T/W &= \frac{0.010\alpha + 0.81}{\alpha - 2.0} + 0.035 \\ &= \frac{0.010(38.7) + 0.81}{38.7 - 2.0} + 0.035 \\ &= 0.063 + 0.035 = 0.068 \end{aligned}$$

Rolling resistance on level ground (M101):

$$P_T = P_T/W(nW) = 0.068(2000 \text{ lb}) = 136 \text{ lb}$$

- (4) Rolling resistance on 10 percent slope:

$$\begin{aligned} &\text{Rolling resistance on 10 percent slope} \\ &= P_T/W(nW) + \text{slope}(nW) \\ &= 136 \text{ lb} + 0.10(2000 \text{ lb}) = 336 \text{ lb} \end{aligned}$$

- (5) Is maximum drawbar pull of an M37 on 10 percent slope greater than the rolling resistance of an M101 trailer on a 10 percent slope under the conditions

specified? Maximum drawbar pull of an M37 on a 10 percent slope = 800 lb. Rolling resistance of M101 on a 10 percent slope = 336 lb. The M37's drawbar pull is greater.

d. Conclusion.

The vehicle's drawbar pull exceeds the trailer's rolling resistance, so the vehicle-trailer combination will be mobile under the conditions specified. If the calculations are carried further, it can be seen that the vehicle-trailer combination would be immobilized on a slope of 15 to 16 percent, i.e. let (M37 weight)(slope) + (M101 weight)(slope) + rolling resistance of M101 = maximum drawbar pull.  $(6000 \text{ lb})(\text{slope}) + (2000 \text{ lb})(\text{slope}) + 136 \text{ lb} = 1400 \text{ lb}$   
 $(8000 \text{ lb})(\text{slope}) = 1264 \text{ lb}$   
 $\text{Slope} = 0.158$

Example 5: Selection of Vehicle Drive Mode  
Based on Performance Parameters

8. An all-wheel-drive vehicle has definite advantages over vehicles with similar nonpowered elements. The relations of the pull and towed coefficients to the basic prediction term for sand can be used to show the advantages gained by powering all the wheels. The M37 of example 4 is appropriate for this demonstration, since it can be used either as a 4x4 or as a 4x2 vehicle (i.e. the front axle can be engaged manually).

a. Given.

Soil type: air-dry desert sand

Soil strength  $G$  (minimum) = 20

M37, 4x4, 3/4-ton truck

Gross vehicle weight  $nW = 6000 \text{ lb}$

Number of wheels  $n = 4$

Wheel load  $W = 1500 \text{ lb}$

9.00-16 tires:

$$b = 9.2 \text{ in.}, \quad d = 34.0 \text{ in.}, \quad (bd)^{3/2} = 5530 \text{ in.}^3, \\ \delta/h = 0.35$$

b. Find.

Maximum pull coefficient of and/or slope negotiable by M37: (1) as a 4x4 vehicle and (2) as a 4x2 vehicle.

(1) 4x4 configuration

From example 4,  $\alpha = 25.8$

$$P/W = 0.234$$

(2) 4x2 configuration

$P/W = (\text{maximum drawbar pull of rear wheels minus rolling resistance of front wheels}) \div \text{gross vehicle weight}$

(a) Maximum drawbar pull of rear wheels:

From example 4,  $P/W = 0.234$

Total weight of rear axle = 3000 lb

$$\text{Maximum drawbar pull} = 0.234(3000 \text{ lb}) = 700 \text{ lb}$$

(b) Rolling resistance of front wheels:

From example 4,  $\alpha = 25.8$

From plate 23,  $P_T/W = 0.080$  ; or from the equation for towed wheels in plate 23:

$$P_T/W = \frac{0.010\alpha + 0.81}{\alpha - 2.0} + 0.035$$

$$P_T/W = \frac{0.010(25.8) + 0.81}{25.8 - 2.0} + 0.035$$

$$P_T/W = 0.045 + 0.035 = 0.080$$

Total weight on front axle = 3000 lb

Total rolling resistance on front wheels

$$= (0.080)(3000 \text{ lb}) = 240 \text{ lb}$$

(c)  $P/W$  and/or slope negotiable = [(a) - (b)]

$$\div \text{gross vehicle weight} = (700 \text{ lb} - 240 \text{ lb})$$

$$\div 6000 \text{ lb} = 0.077$$

c. Conclusion.

The 4x4 will greatly outperform the 4x2. The former

could negotiate slopes as steep as 23 percent, whereas the 4x2 would be immobilized on slopes greater than 7 percent.

# Related Reports

Report No.	Title	Date
TR 3-516	<u>Deflection of Moving Tires, Report 1, A Pilot Study on a 12 X 22.5 Tubeless Tire</u>	July 1959
TR 3-516	<u>Deflection of Moving Tires, Report 2, Tests with a 12.00-22.5 Tubeless Tire on Asphaltic Concrete, Sand, and Gravel, 1959-1960</u>	Aug 1961
TR 3-516	<u>Deflection of Moving Tires, Report 3, Center-Line Deflection Studies Through July 1963</u>	May 1965
TR 3-545	<u>Stresses Under Moving Vehicles, Report 2, Wheeled Vehicles (M2C), Clean and Fat Clay, 1957</u>	May 1960
TR 3-545	<u>Stresses Under Moving Vehicles, Report 3, Tracked Vehicles (M2C, D4, and M7) on Fat Clay, 1956</u>	July 1960
TR 3-569	<u>Tests with Rigid Wheels, Report 1, Tests in Fat Clay, 1958</u>	May 1961
TR 3-639	<u>Strength-Moisture-Density Relations of Fine-Grained Soils in Vehicle Mobility Research</u>	Jan 1964
TR 3-666	<u>Performance of Soils Under Tire Loads, Report 1, Test Facilities and Techniques</u>	Jan 1965
TR 3-666	<u>Performance of Soils Under Tire Loads, Report 2, Analysis of Tests in Yuma Sand Through August 1962</u>	Aug 1965
TR 3-666	<u>Performance of Soils Under Tire Loads, Report 3, Tests in Clay Through November 1962</u>	Feb 1966
TR 3-666	<u>Performance of Soils Under Tire Loads, Report 4, Analysis of Tests in Sand from September 1962 Through November 1963</u>	Feb 1966
TR 3-666	<u>Performance of Soils Under Tire Loads, Report 5, Development and Evaluation of Mobility Numbers for Coarse-Grained Soils</u>	July 1967
TR 3-666	<u>Performance of Soils Under Tire Loads, Report 6, Effects of Test Techniques on Wheel Performance</u>	Oct 1967
TR 3-666	<u>Performance of Soils Under Tire Loads, Report 7, Extension of Mobility Prediction Procedures to Rectangular-Cross-Section Tires in Coarse-Grained Soil</u>	Apr 1972
MP 4-247	<u>Vehicle Mobility on Soft Soils</u>	Feb 1966
MP 4-247	<u>Performance of Soils Under Tire Loads, Report 8, Effects of Test Techniques on Wheel Performance</u>	Oct 1967